Black Holes at the LHC

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BROWN UNIVERSITY

3rd COST WG Meeting

April 13, 2011

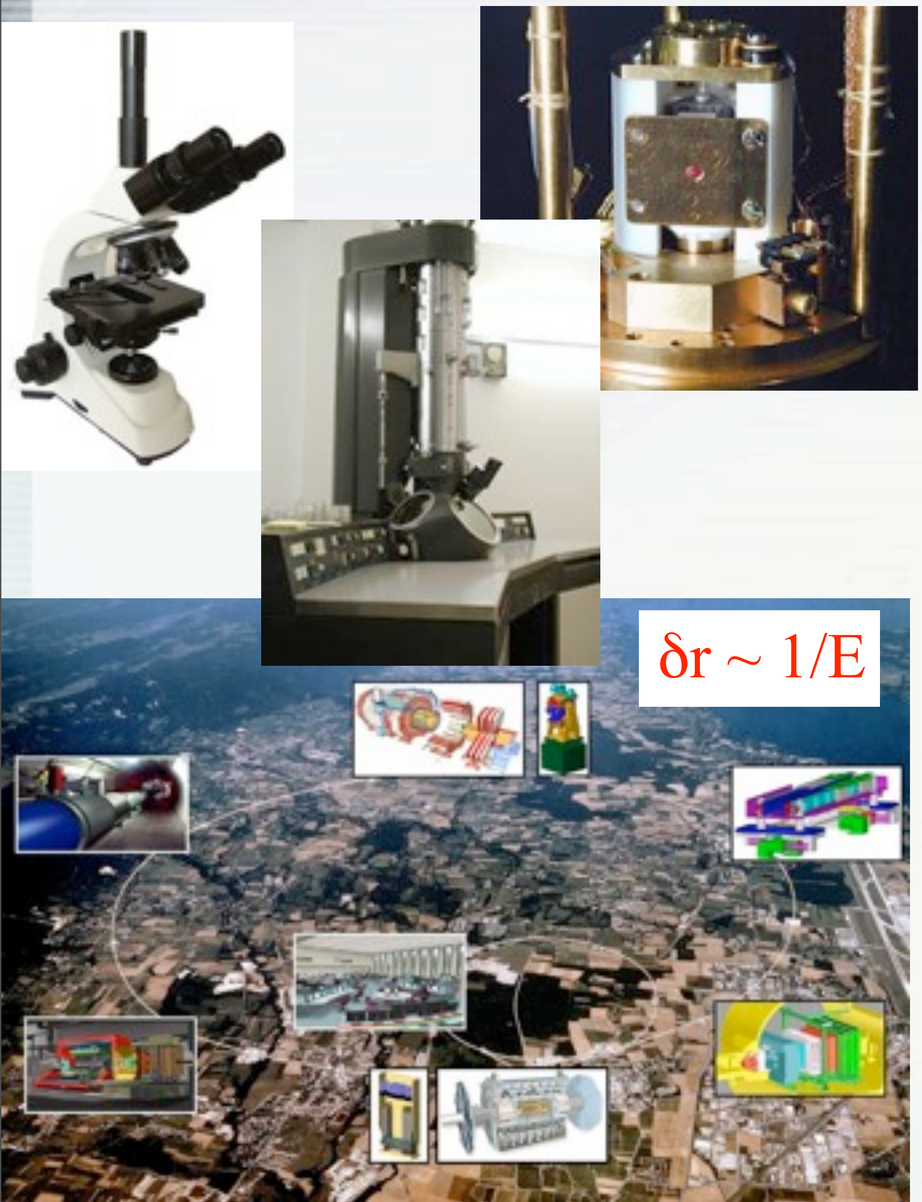
Outline

- *Per Partis ad Astra*
- *The Hierarchy Problem*
- *The LHC & Detectors*
- *Setting the scene: Extra Dimensional Paradigms*
- *Collider Phenomenology*
- *Current Limits*
- *The LHC Discovery Reach*
- *Black Holes at the LHC*
- *Conclusions*

Astro-Particle Physics

- Last decade emphasized remarkable connection between the astrophysics and particle physics:
  - Searches for dark matter
  - QFT connections to early universe and inflation
  - Black hole thermodynamics
  - The "landscape" of string theory
- The more we study these seemingly different subjects, the more connections we discover
  - Physics at the very large distances may be inherently connected to the physics at the shortest ones
- More similarities:
  - Microscopes vs. telescopes
  - Large international collaborations
  - Complicated detectors
- We are (hopefully!) doing the things via two complementary

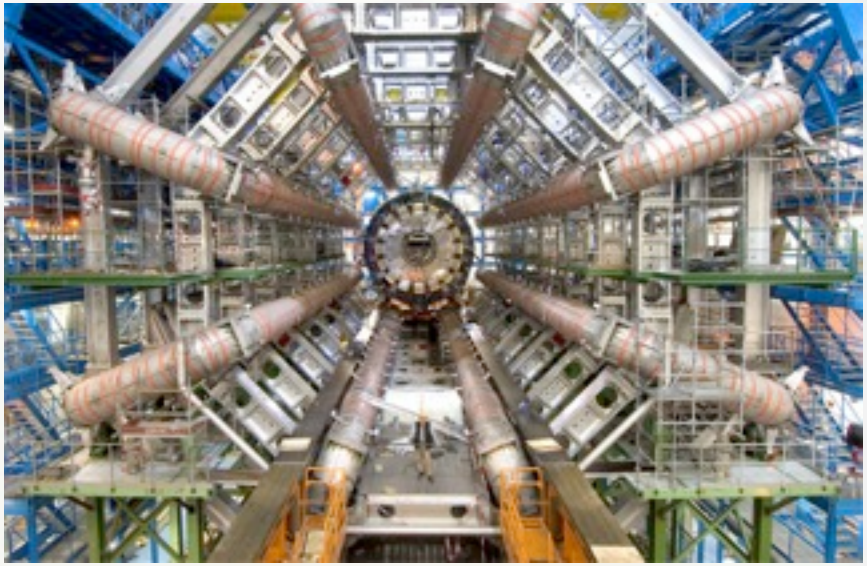
Microscopes vs. Telescopes



$\delta r \sim 1/E$

$\Delta\theta = 1.22\ \lambda/D$

Beautiful Instruments



Spectacular Launches

Large Hierarchies Tend to Collapse...

SM: 10^{-38}
fine-tuning

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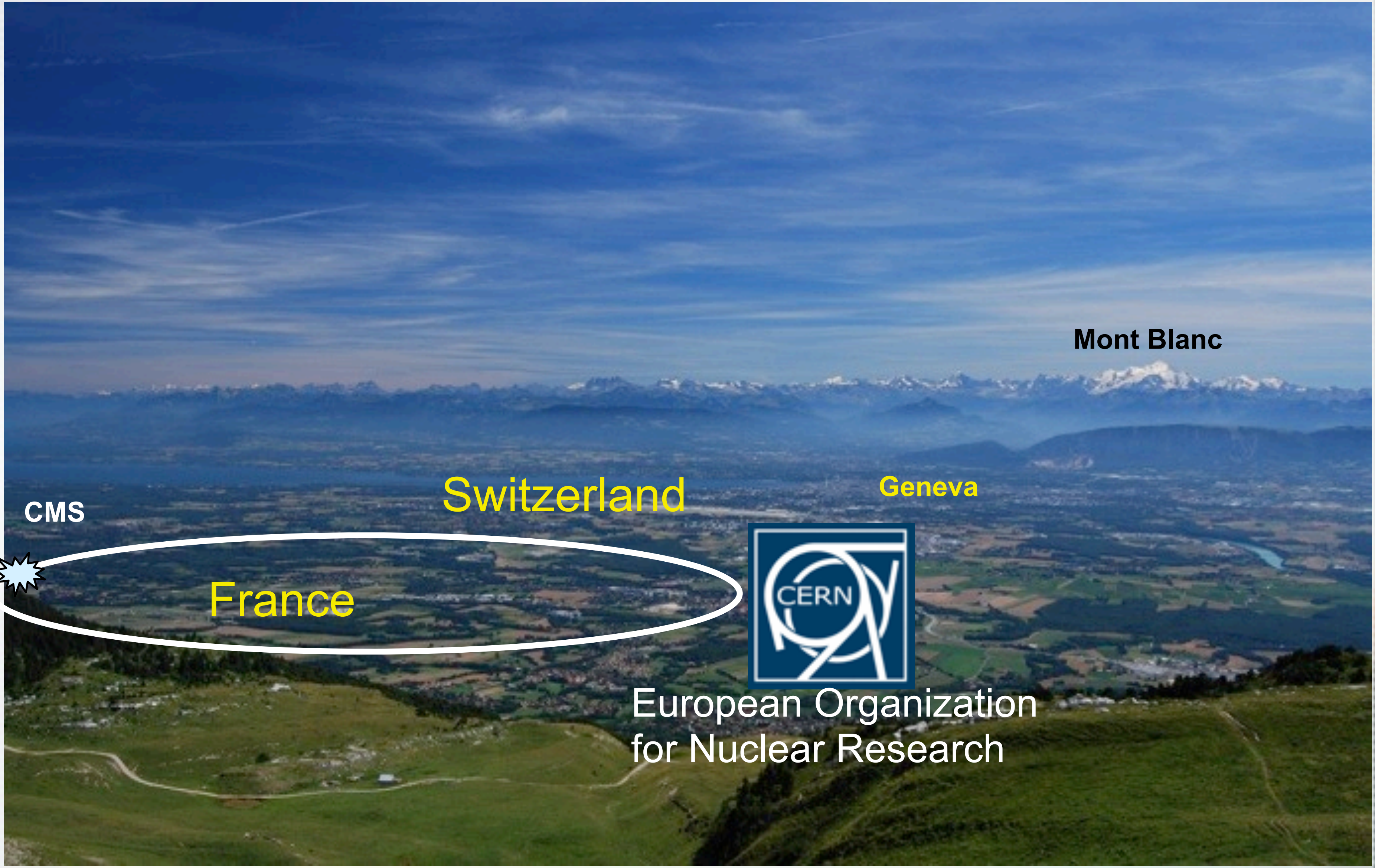
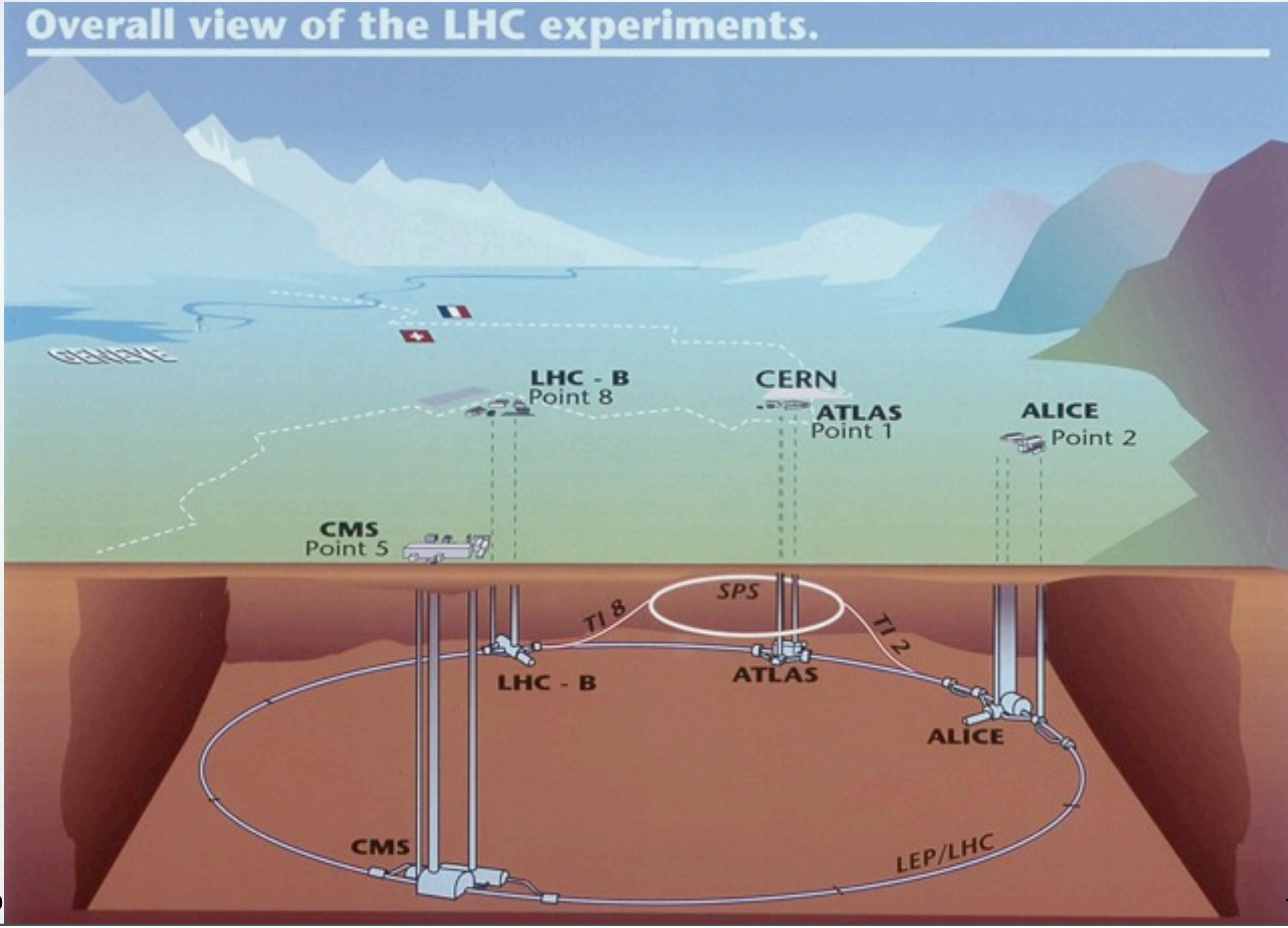
  (Food for thought: is it really numerology?)

The LHC Locale



The LHC - Aerial View

The LHC Experiments



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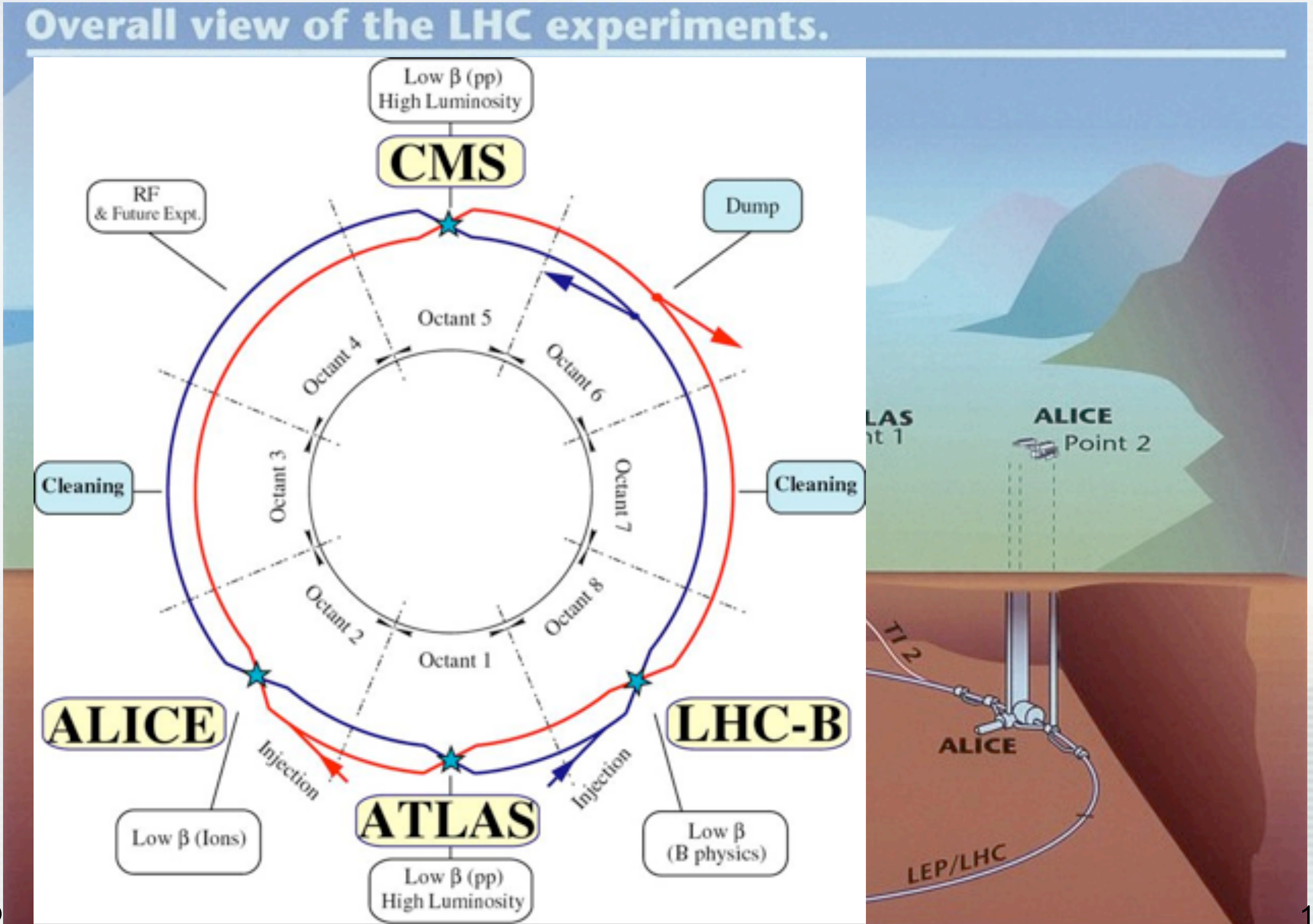

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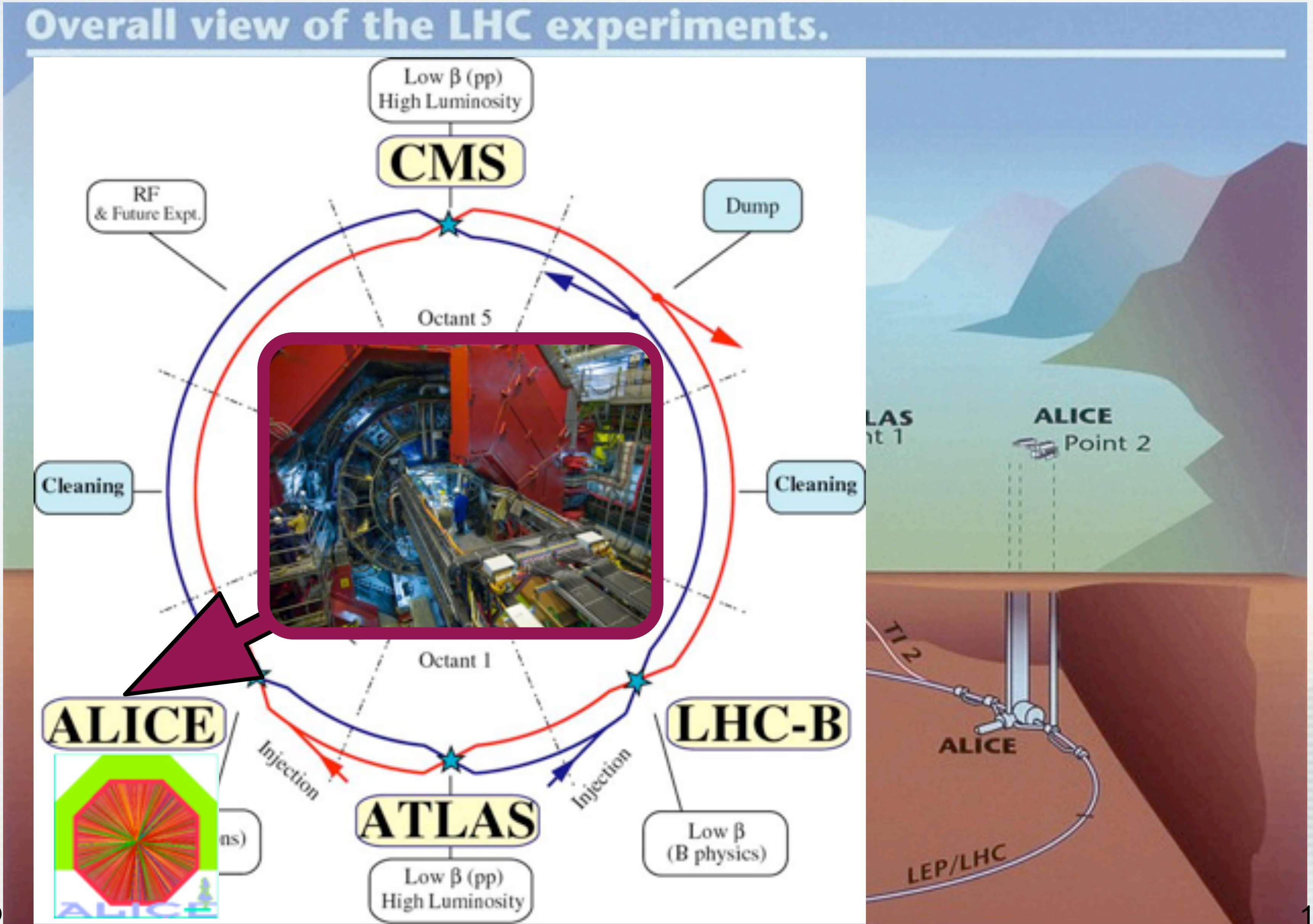

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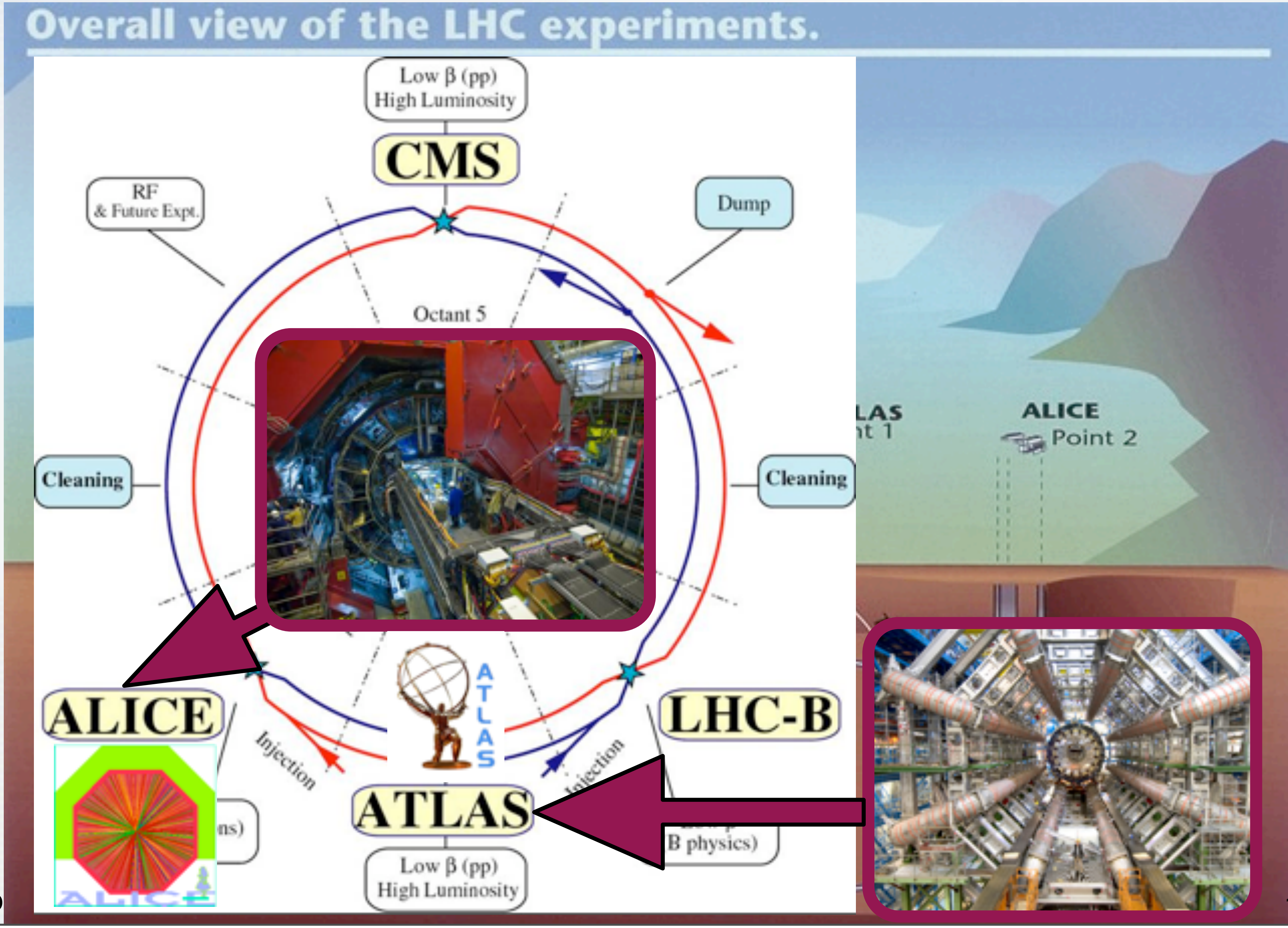

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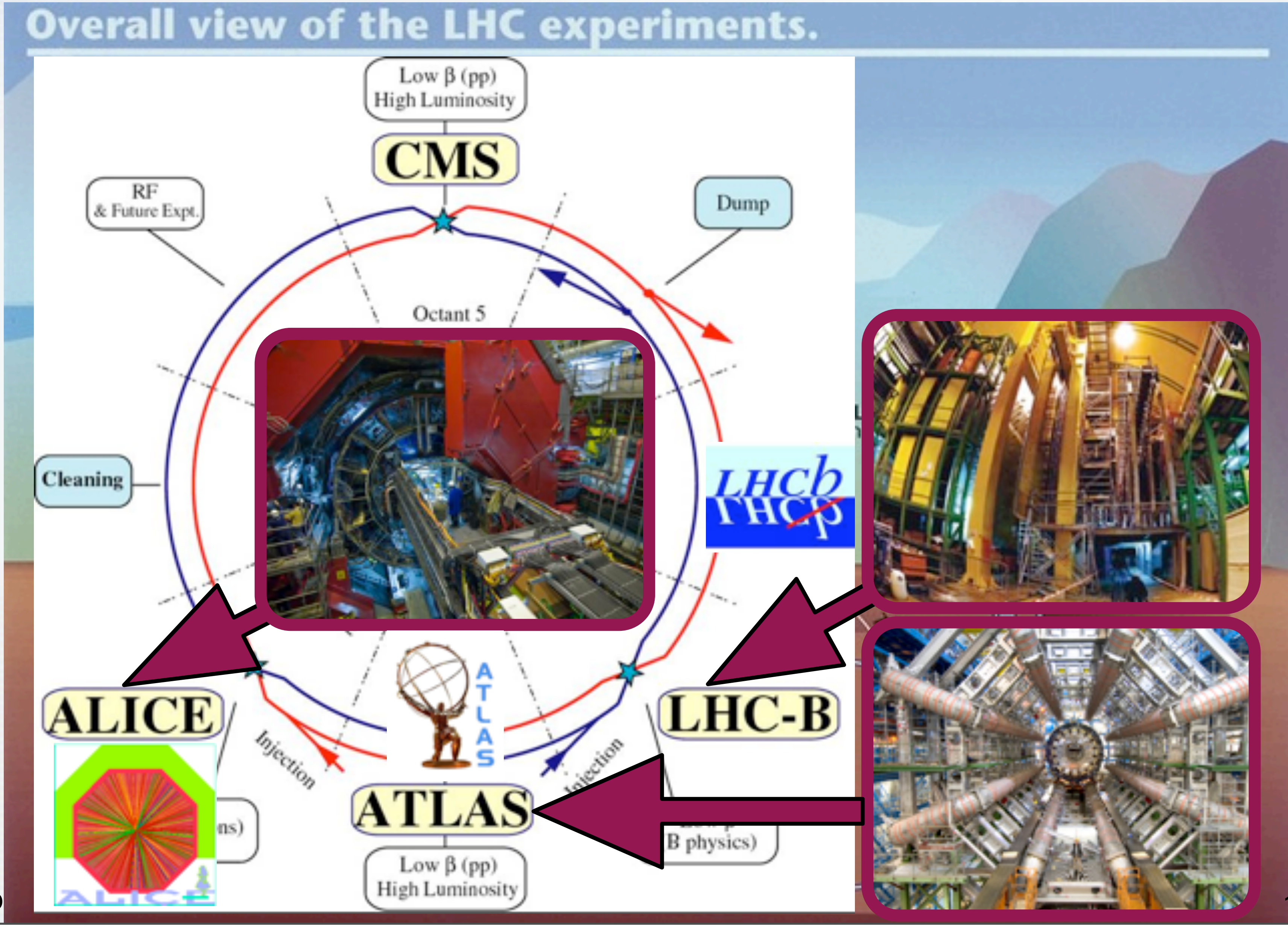

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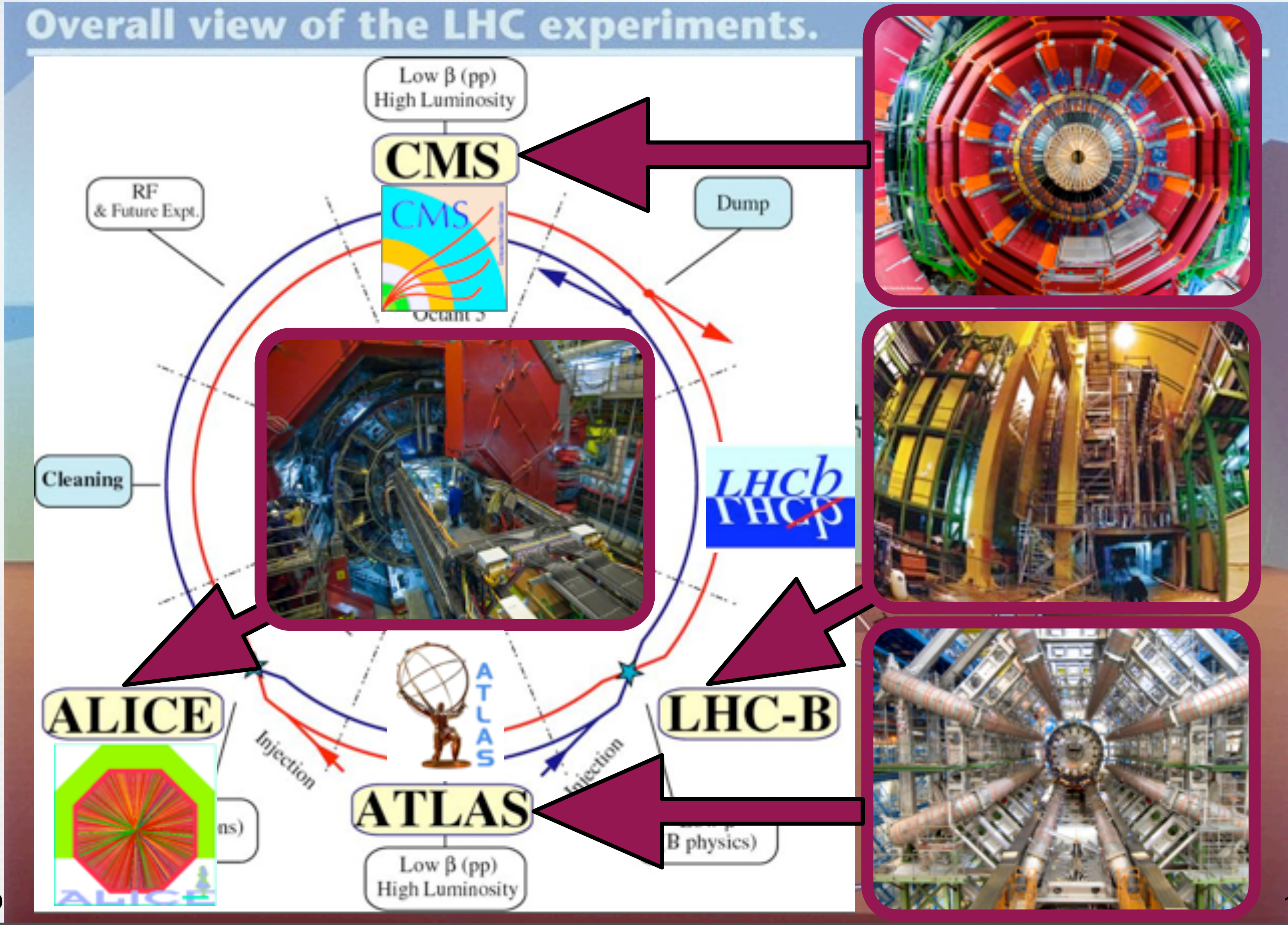
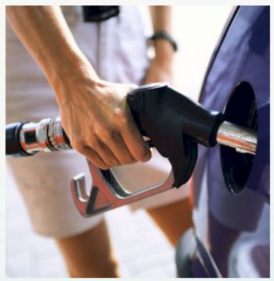


LHC: facts

- Energy: 7 x 7 TeV (started at 3.5 x 3.5 TeV), i.e. 7 (3.5) times more powerful than the previous big machine, the Tevatron
- Circumference: 26.7 km
- Number of proton bunches: 2808 x 2808; 1.15×10^{11} protons/bunch
- Magnetic field: 8.3 T
- Luminosity: 10^{34} $cm^{-2}s^{-1}$ = 10^{-2} $pb^{-1}s^{-1}$ = 7 top pairs/s = 100 W(eν)/s
- Energy stored in magnets: 10 GJ = A380 at cruise speed of 700 km/h. Can heat and melt 12 tons of copper!

- Energy stored in a single beam: 360MJ = 90 kg of TNT = 8 liters of gas = 15 kg of chocolate

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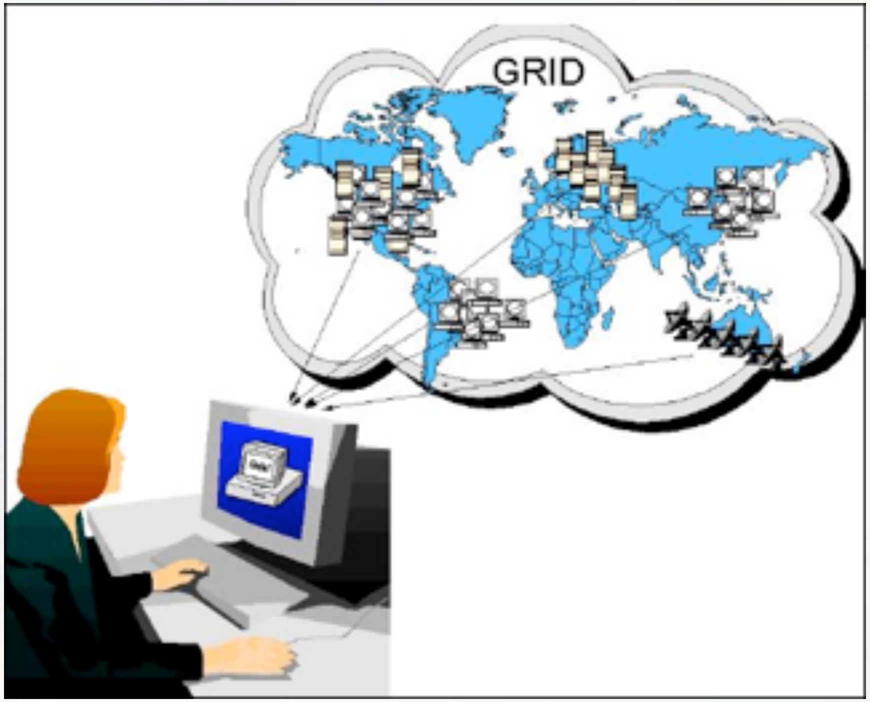
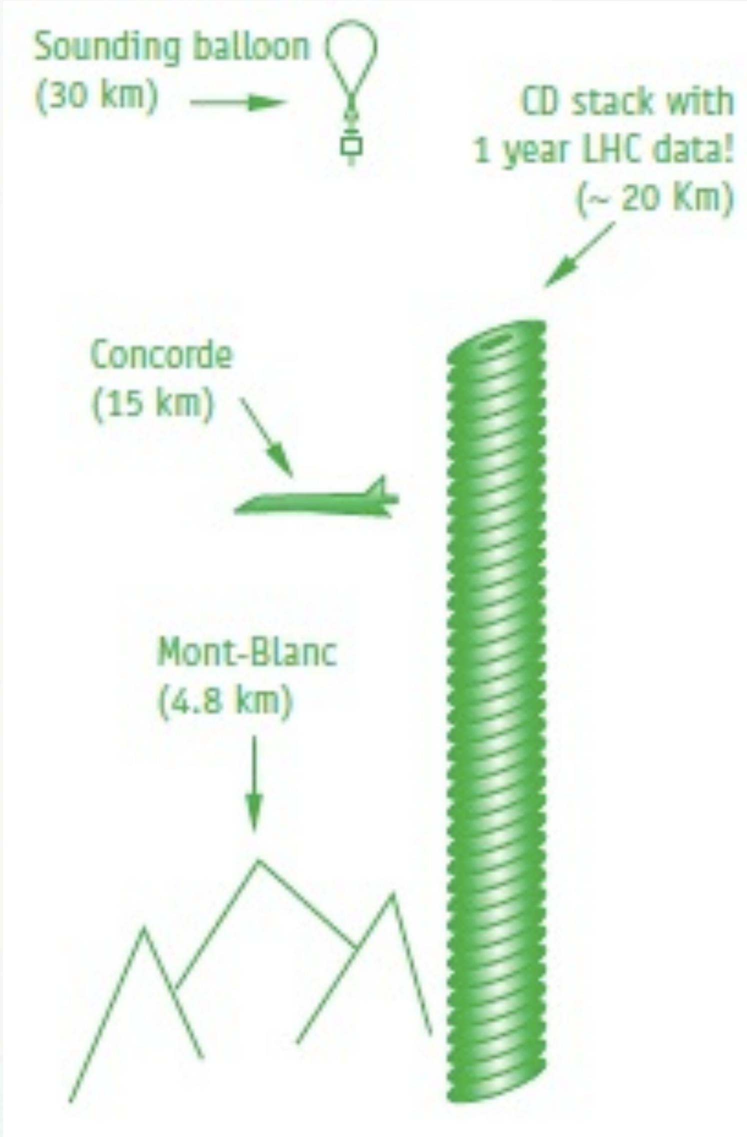
- The cost of the machine and detectors is \$10B CHF or \$9B
- Everything about LHC is at least 10 times bigger than ever attempted before!

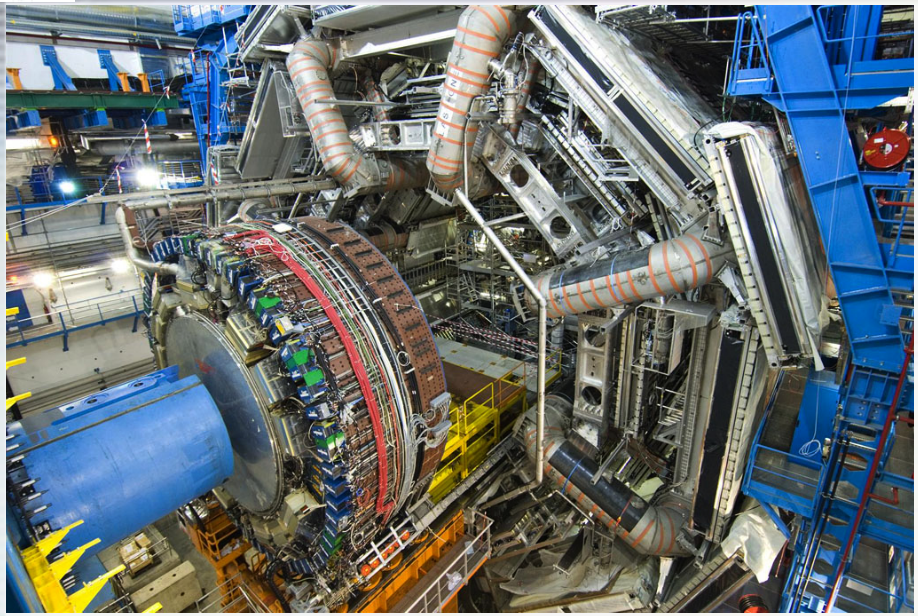
How Much Data Does it Produce?

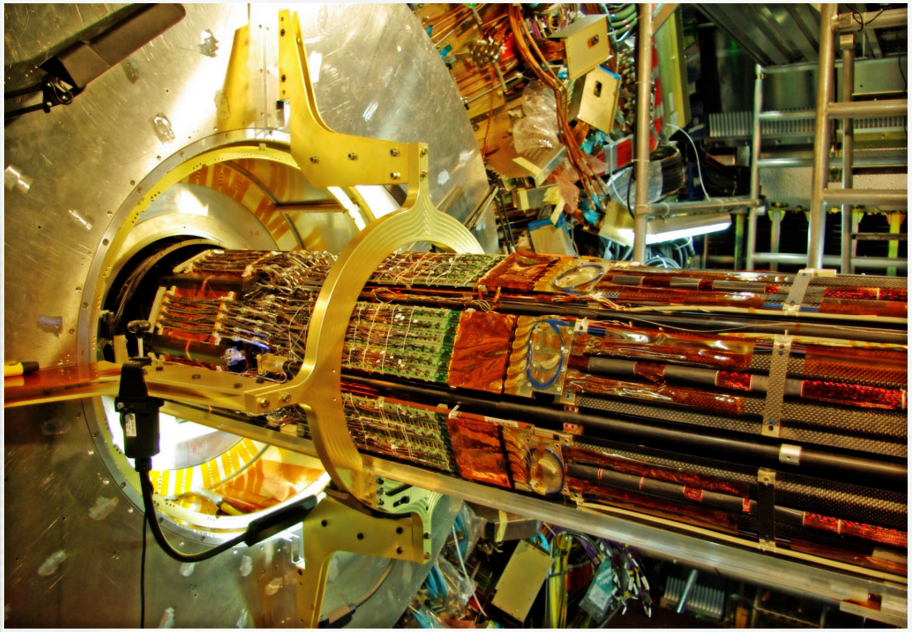
- Nearly 1 GB of data is recorded every second
  - 15,000 TB/year = 15 PB/year
  - It's like recording a DVD every 4 sec
  - Enough to fill your hard drive in 2 min
- Processed all around the world via LHC Computing Grid



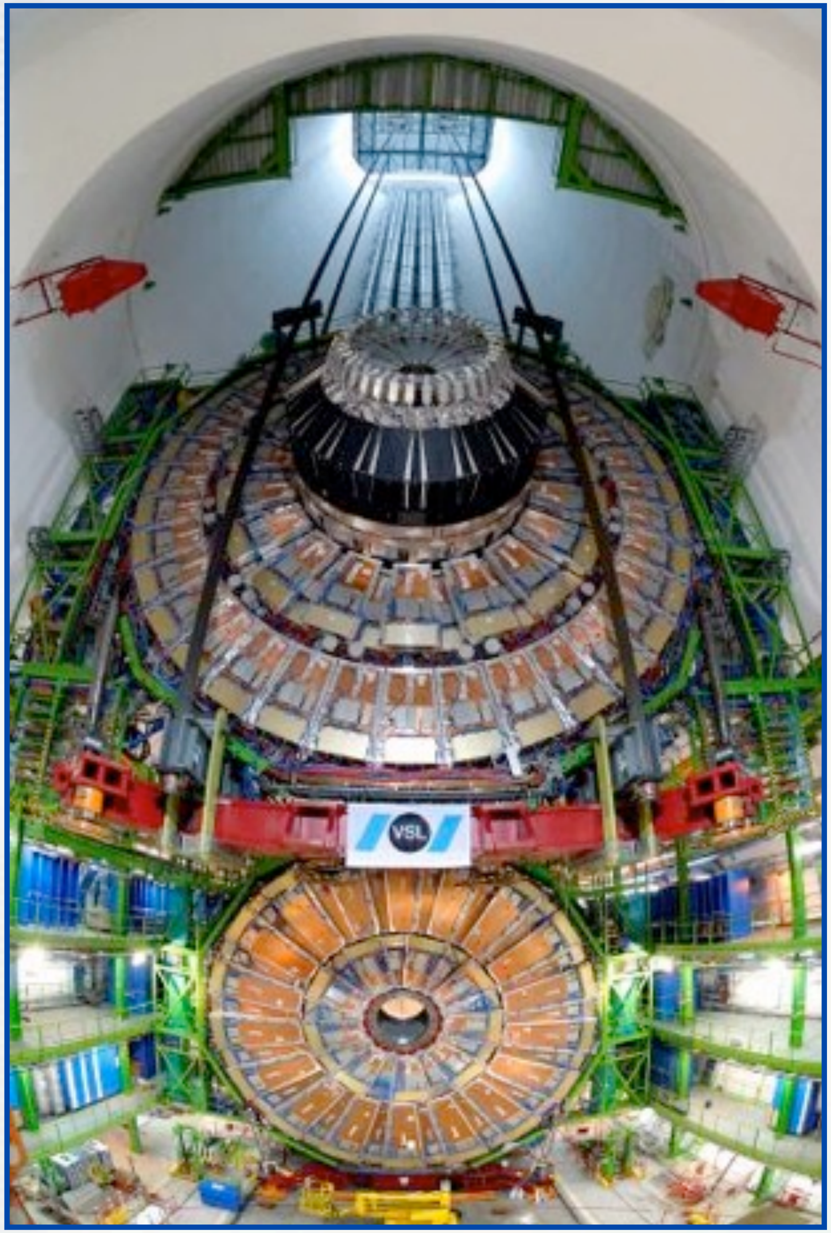


ATLAS in 2008

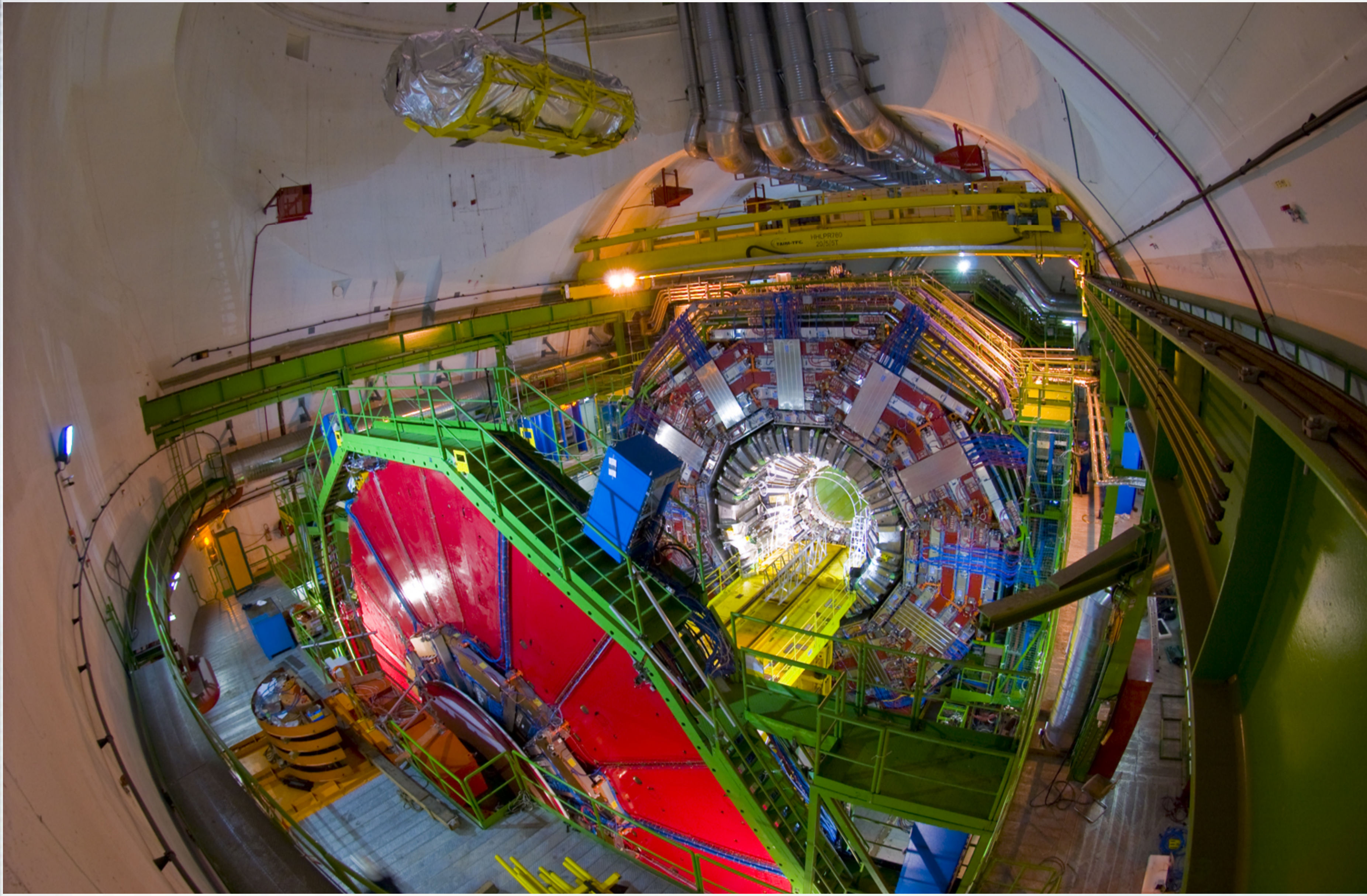




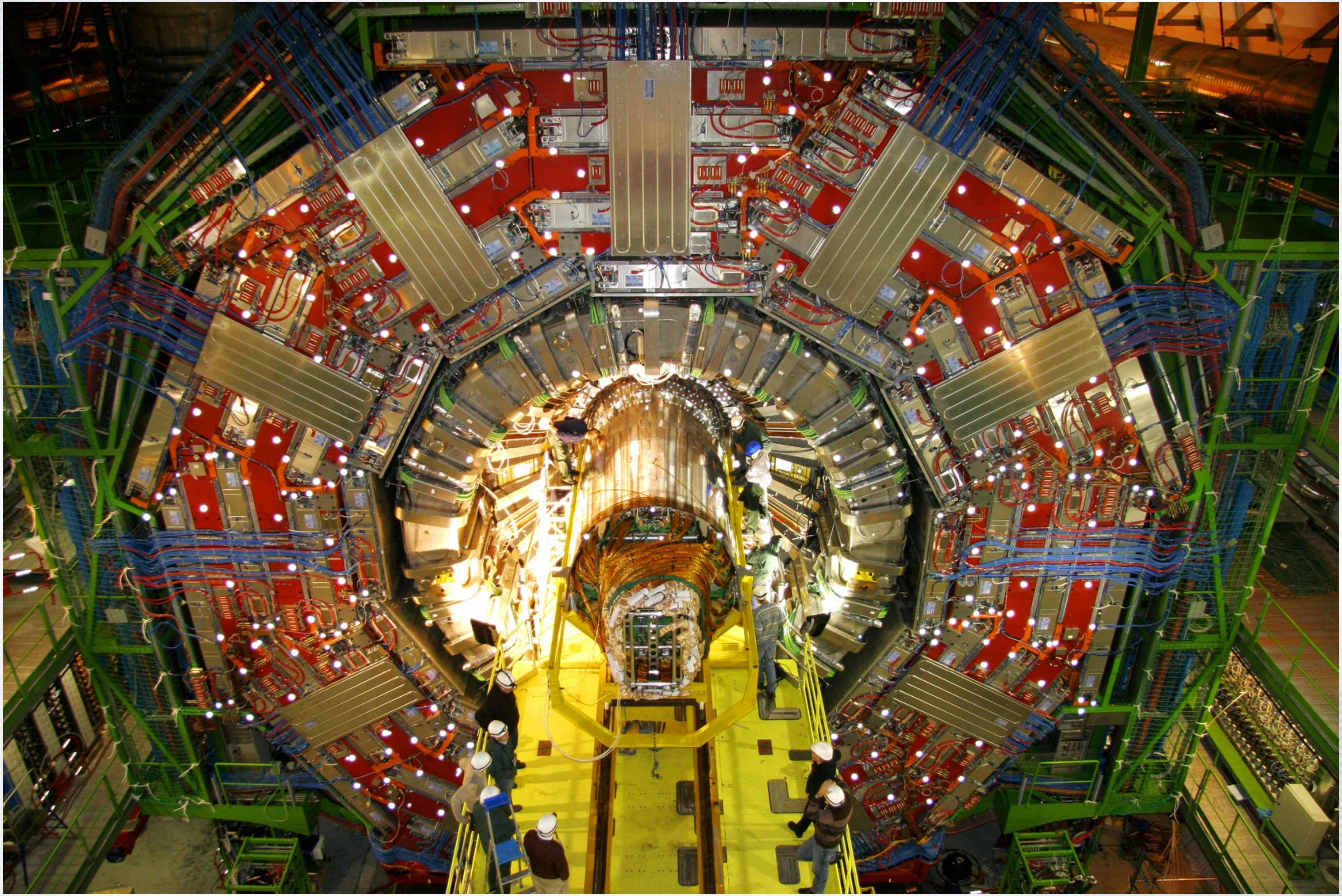
Assembling the CMS



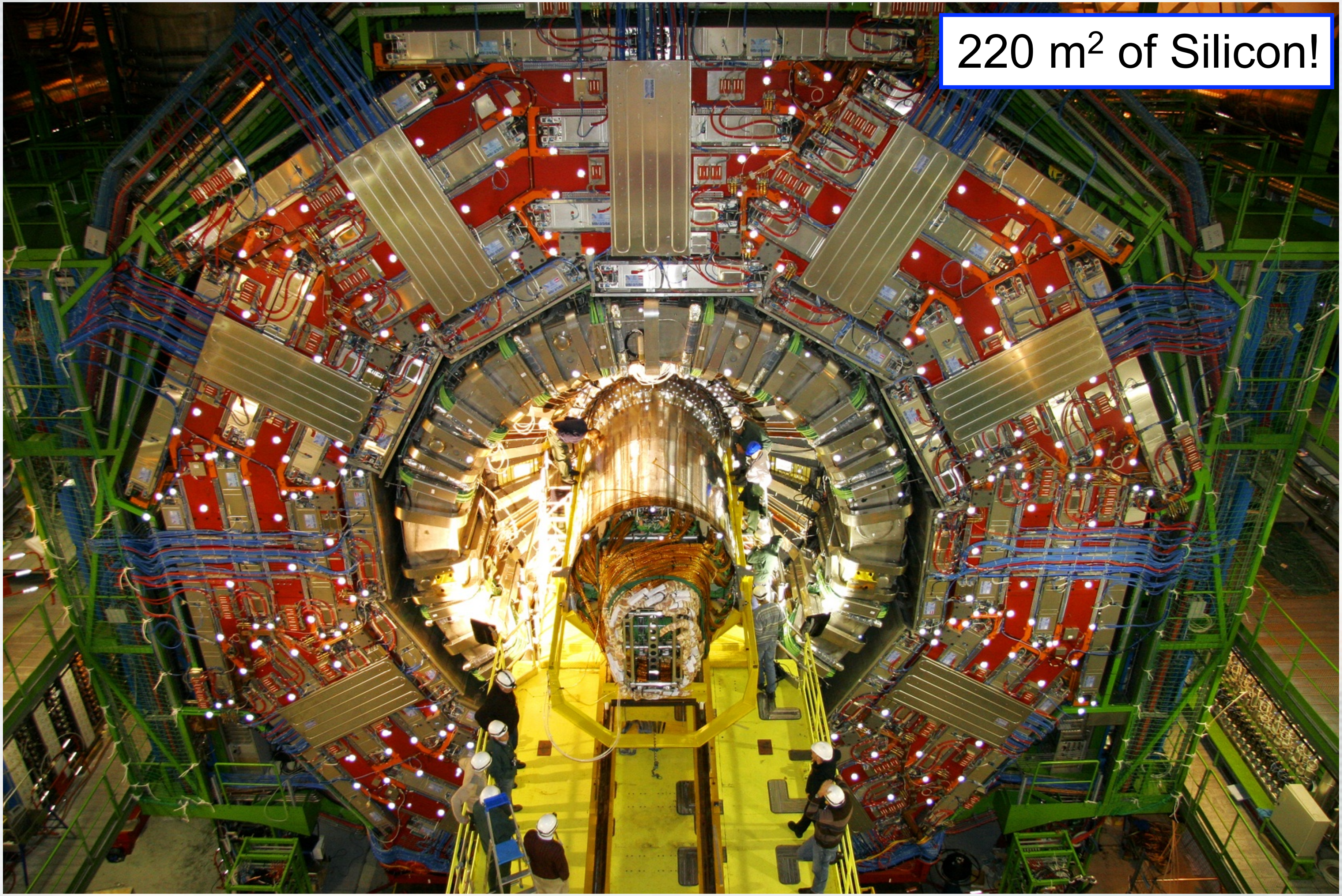
CMS in December, 2007



CMS in January 2008



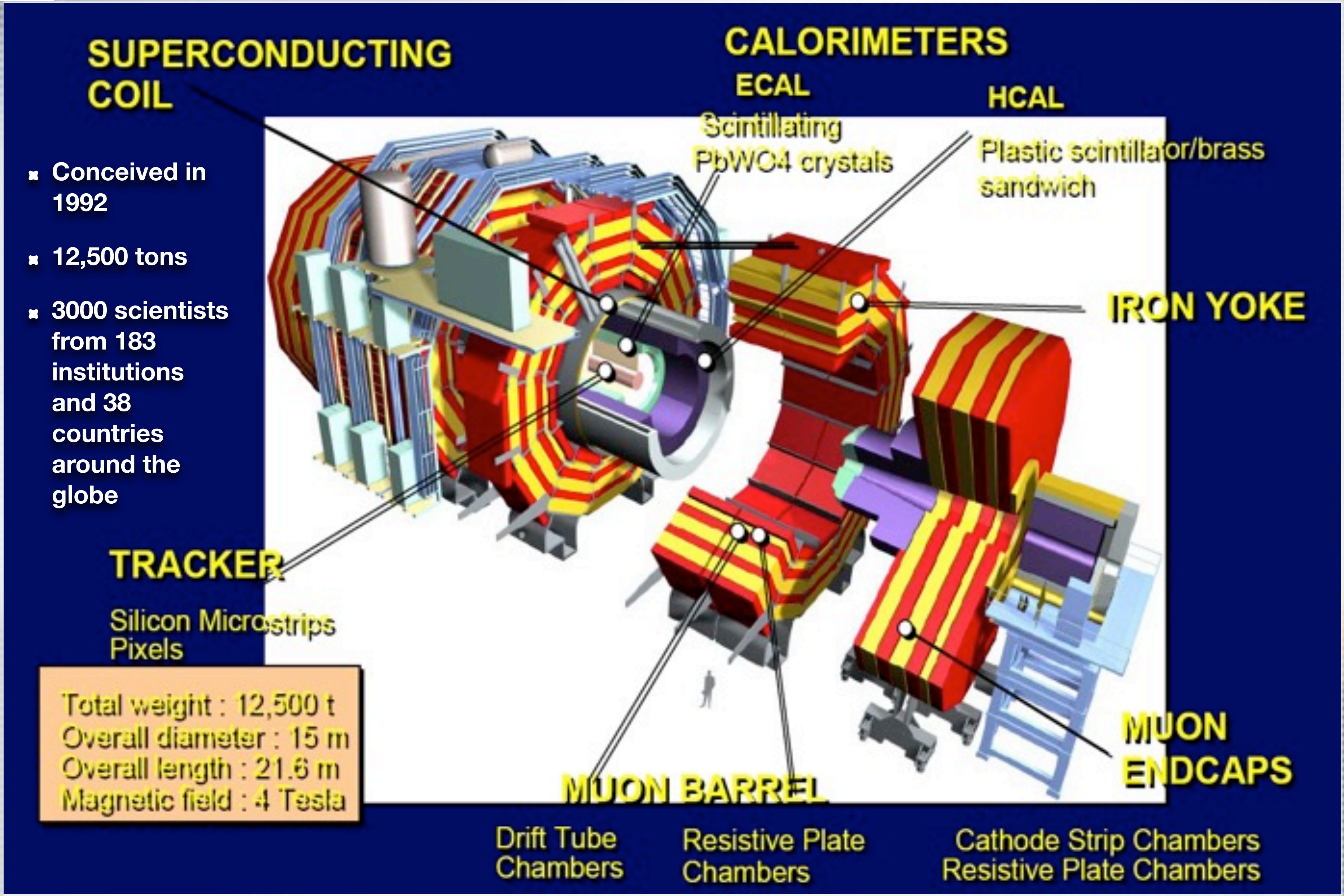
CMS in January 2008



CMS Explained

A 100 MP digital camera,
which takes 40 million frames/sec!

- Conceived in 1992
- 12,500 tons
- 3000 scientists from 183 institutions and 38 countries around the globe

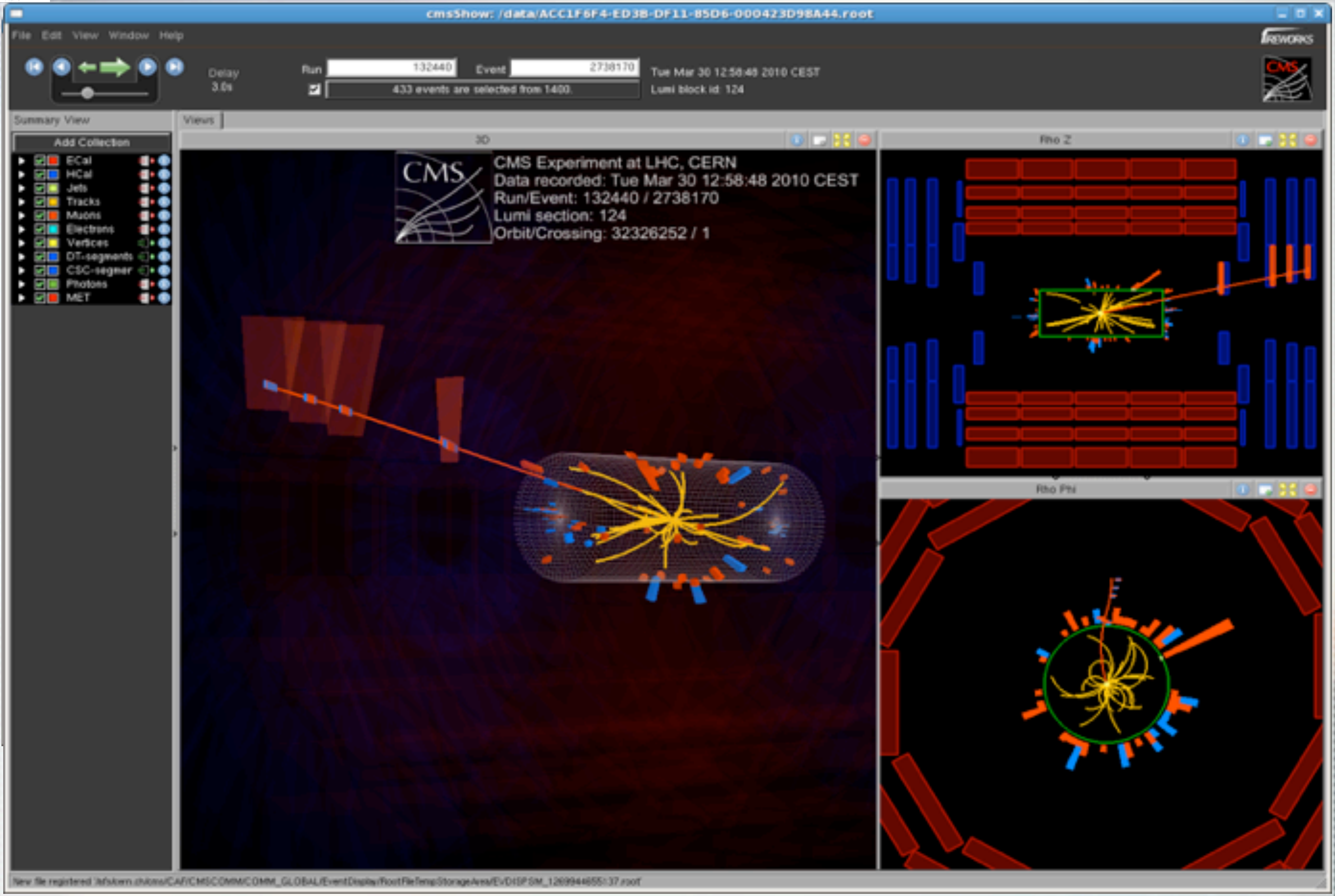


First 7 TeV Collisions - 30/3/10

Accelerator Control Room

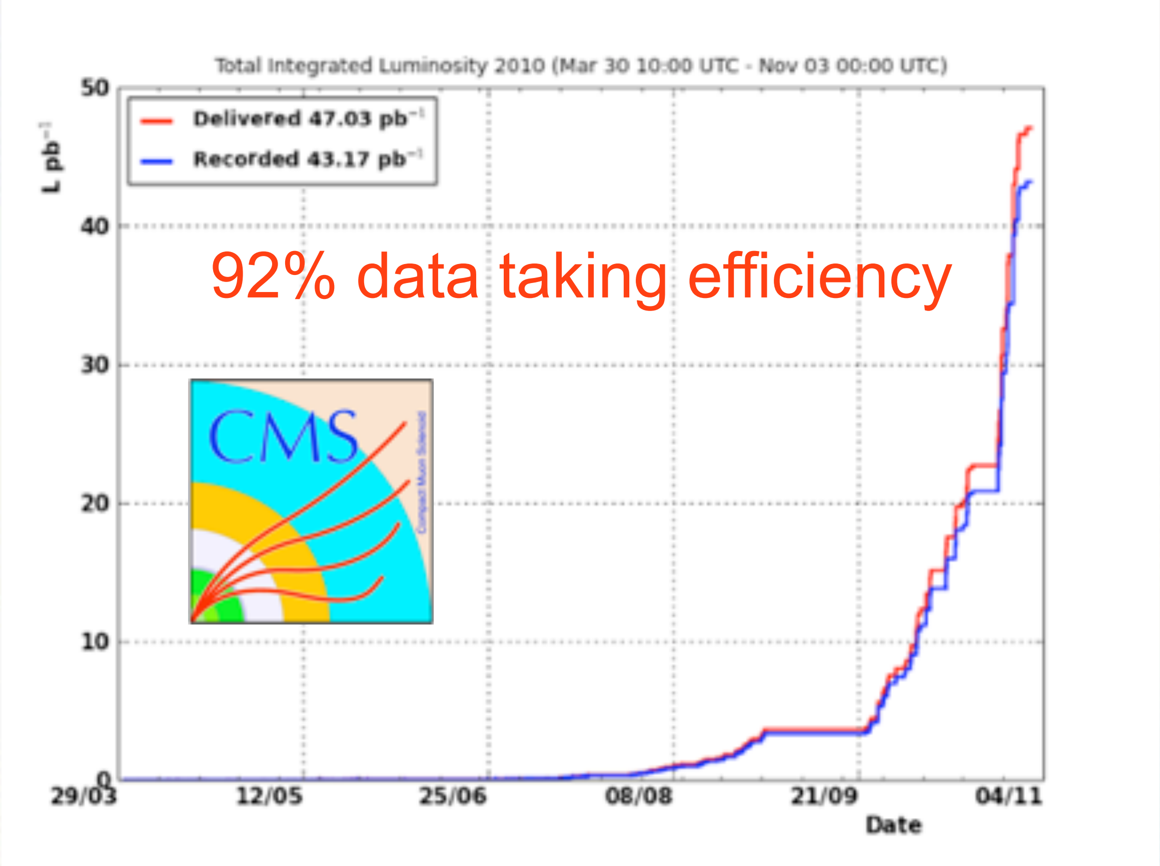
First 7 TeV Events in CMS

First 7 TeV Events in CMS



The LHC Luminosity Profile

- Delivered 50 pb^{-1} in 2010
- Expect ~5 fb^{-1} in 2011 and ~10 fb^{-1} by the end of 2012
- Keep running at 7 TeV in 2011; possibly 8 TeV next year
- Shut down for ~1.5 years year and go to ~14 TeV in 2014



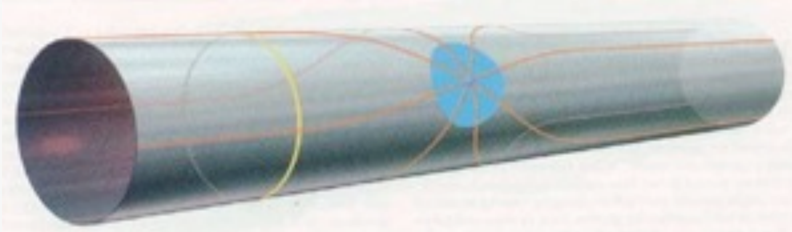
1998: Large Extra Dimensions

- But: what if there is no other scale, and SM model is correct up to M_{Pl}?
  - Give up naturalness: inevitably leads to anthropic reasoning
  - Radically new approach – Arkani-Hamed, Dimopoulos, Dvali (ADD, 1998): maybe the fundamental Planck scale is only ~ 1 TeV?!!
- Gravity is made strong at a TeV scale due to existence of *large* (r ~ 1mm – 1fm) extra spatial dimensions:
  - SM particles are confined to a 3D "brane"
  - Gravity is the only force that permeates "bulk" space
- What about Newton's law?

$$V(\rho) = \frac{1}{M_{\rm Pl}^2}\frac{m_1 m_2}{\rho^{n+1}} \to \frac{1}{\left(M_{\rm Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{\rho^{n+1}}$$

- Ruled out for infinite ED, but does not apply for compact ones:

$$V(\rho) \approx \frac{1}{\left(M_{\rm Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^n \rho}, \text{for} \rho \gg r$$



- Gravity is fundamentally strong force, but we do not feel that as it is diluted by the large volume of the bulk space $G'_N = 1/(M_{\rm Pl}^{[3+n]})^2 = 1/M_D^2$; M_D ~ 1 TeV

$$M_D^{n+2} \sim M_{\rm Pl}^2/r^n$$

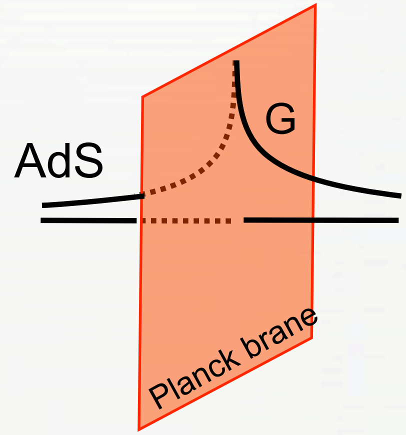
- More precisely, from Gauss's law:

$$r = \frac{1}{\sqrt{4\pi}M_D}\left(\frac{M_{\rm Pl}}{M_D}\right)^{2/n} \sim \begin{cases} 8\times 10^{12} m, & n=1 \\ 0.7 mm, & n=2 \\ 3 nm, & n=3 \\ 6\times 10^{-12} m, & n=4 \end{cases}$$

- Amazing as it is, but as of 1998 no one has tested Newton's law to distances less than ~ 1mm! (Even now it's been tested to only 0.16mm!)
- Thus, the fundamental Planck scale could be as low as 1 TeV for n > 1

Randall-Sundrum Model

- Randall-Sundrum (RS) model [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
  - –One + brane – no low energy effects
  - –Two + and – branes – TeV Kaluza-Klein modes of graviton
  - –Low energy effects on SM brane are given by Λ_π; for kr ~ 10, Λ_π ~ 1 TeV and the hierarchy problem is solved naturally



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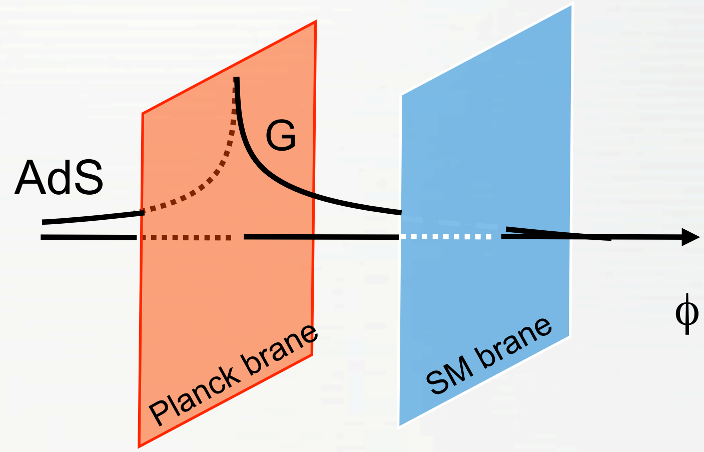

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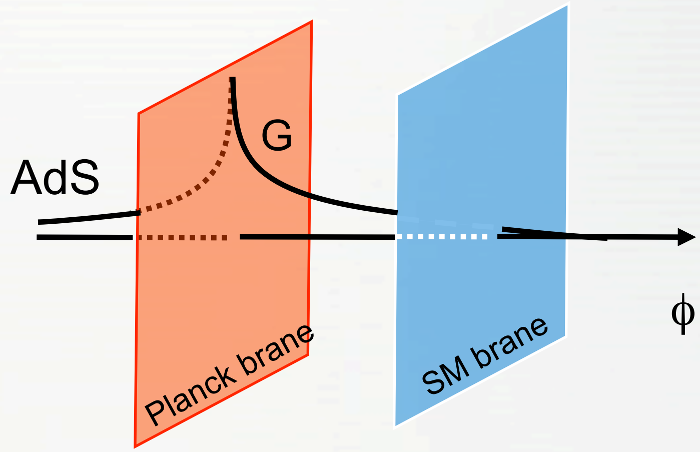
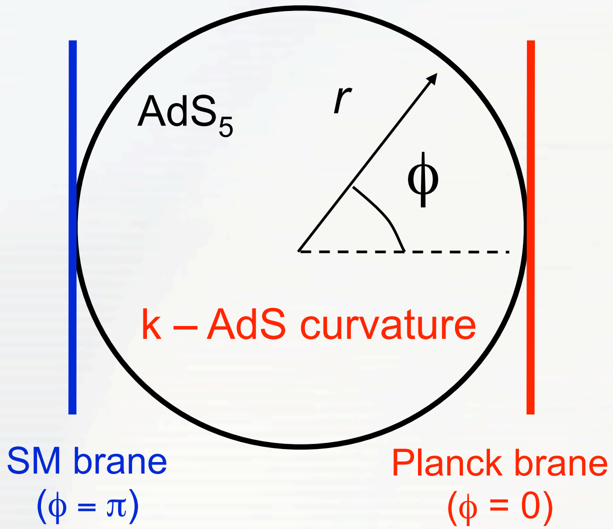




Anti-deSitter space-time metric:

$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$

$$\Lambda_\pi = \overline{M}_{\rm Pl} e^{-kr\pi}$$

Reduced Planck mass:

$$\boxed{\overline{M}_{\rm Pl} \equiv M_{\rm Pl}/\sqrt{8\pi}}$$

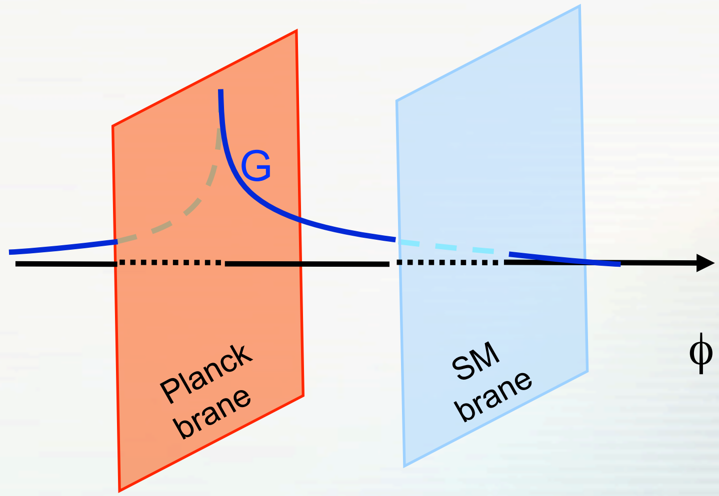
Extra Dimensions: a Brief Summary

ADD Paradigm:

- Pro: "Eliminates" the hierarchy problem by stating that physics ends at a TeV scale
- Only gravity lives in the "bulk" space
- Size of ED's (n=2-7) between ~100 μm and ~1 fm
- Black holes at the LHC and in the UHE cosmic rays
- Con: Doesn't explain why ED are so large

RS Model:

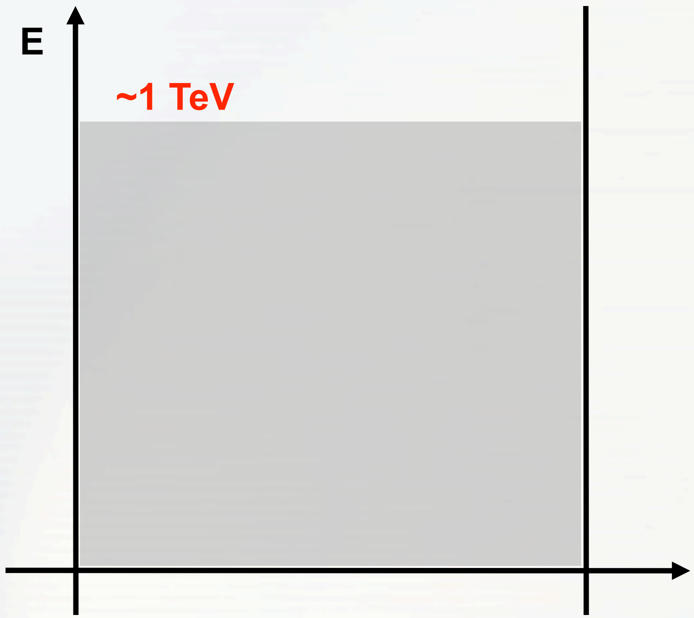
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



ED: Kaluza-Klein Spectrum

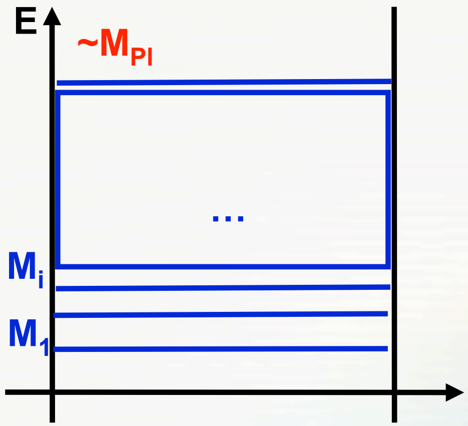
ADD Paradigm:

- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Experimentally can't resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by large number of modes



RS Model:

- "Particle in a box" with special AdS metric
- Energy eigenvalues are given by the zeroes of Bessel function J_1
- Light modes might be accessible at colliders
- Coupling: G_N for the zero mode; $1/\Lambda_\pi^2$ for the others



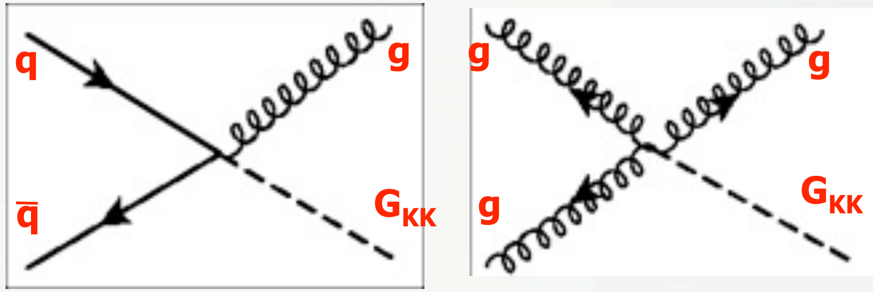
$$M_0 = 0;\ M_i = M_1 \frac{x_i}{x_1} \approx M_1,\ 1.83M_1,\ 2.66M_1,\ 3.48M_1,\ \ldots$$

Collider Signatures for Large ED

- Kaluza-Klein gravitons couple to the energy-momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - Han, Lykken, Zhang [PRD **59**, 105006 (1999)]
  - Giudice, Rattazzi, Wells [NP **B544**, 3 (1999)]
- Graviton emission: direct sensitivity to the fundamental Planck scale M_D
- Virtual effects: sensitive to the ultraviolet cutoff M_S, expected to be $\sim M_D$ (and likely $< M_D$)
- The two processes are complementary

Real Graviton Emission

Monojets at hadron colliders



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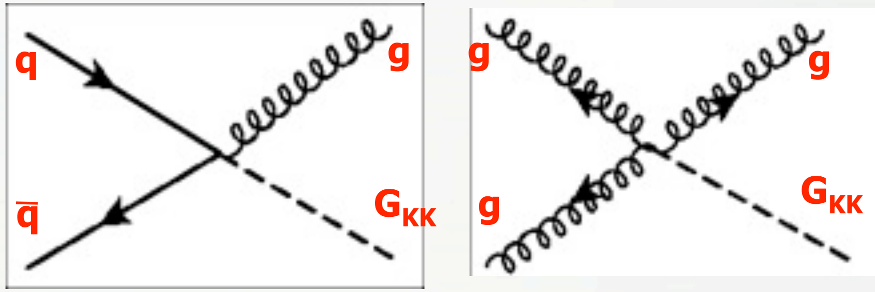
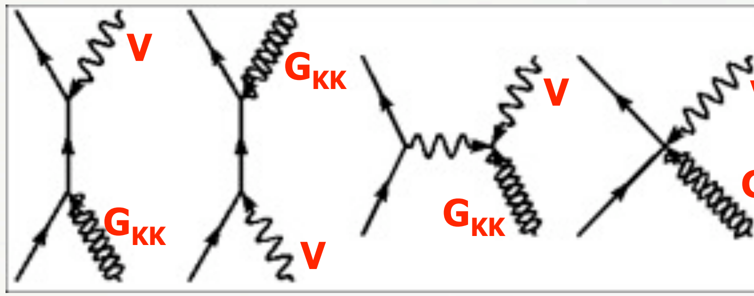


Single VB at hadron or e^+e^- colliders



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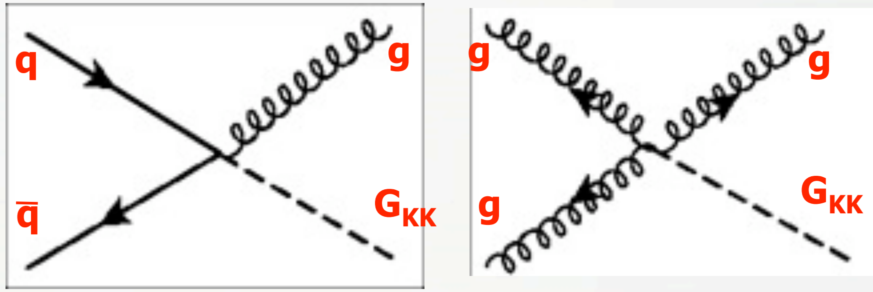

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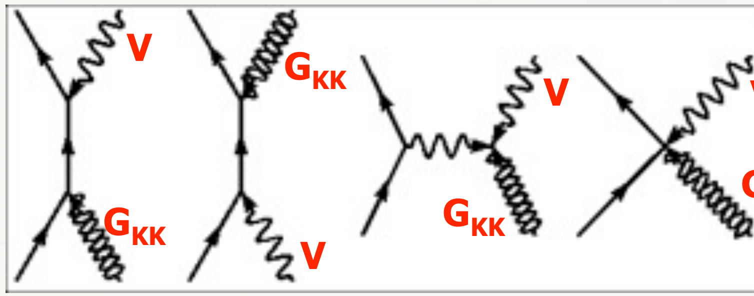
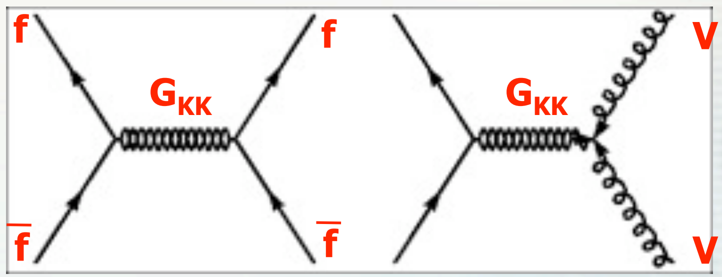


Virtual Graviton Effects

Fermion or VB pairs at hadron or e^+e^- colliders



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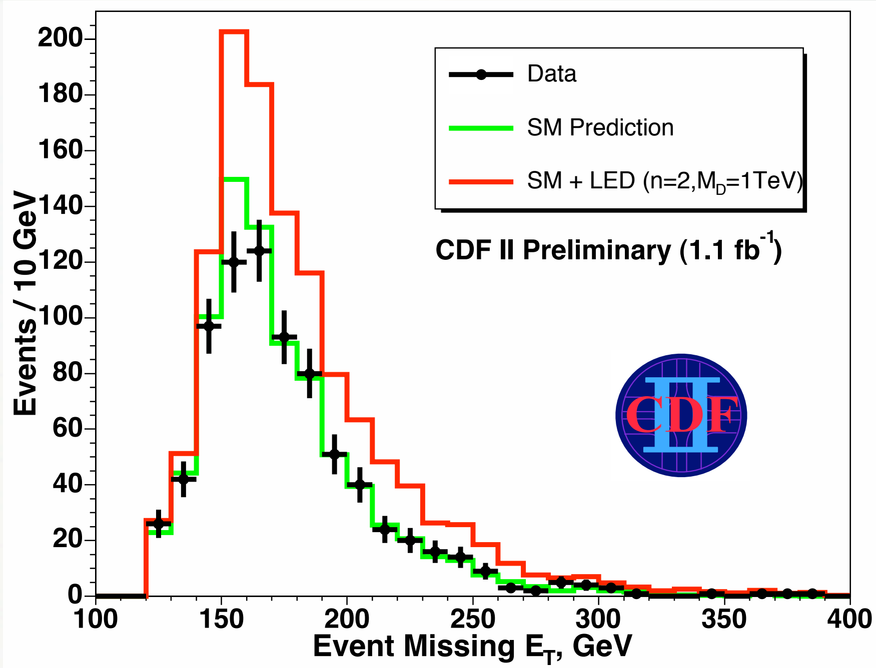
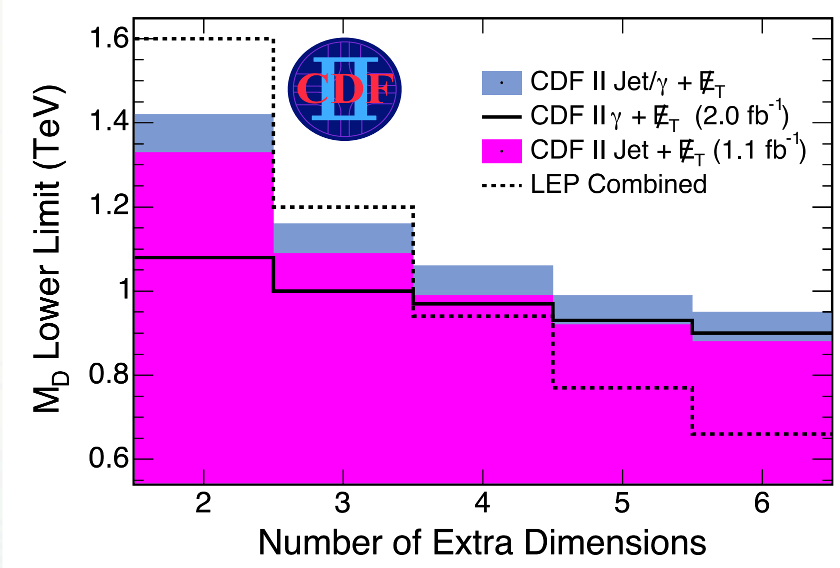
Tevatron: Large ED Search via Monojets

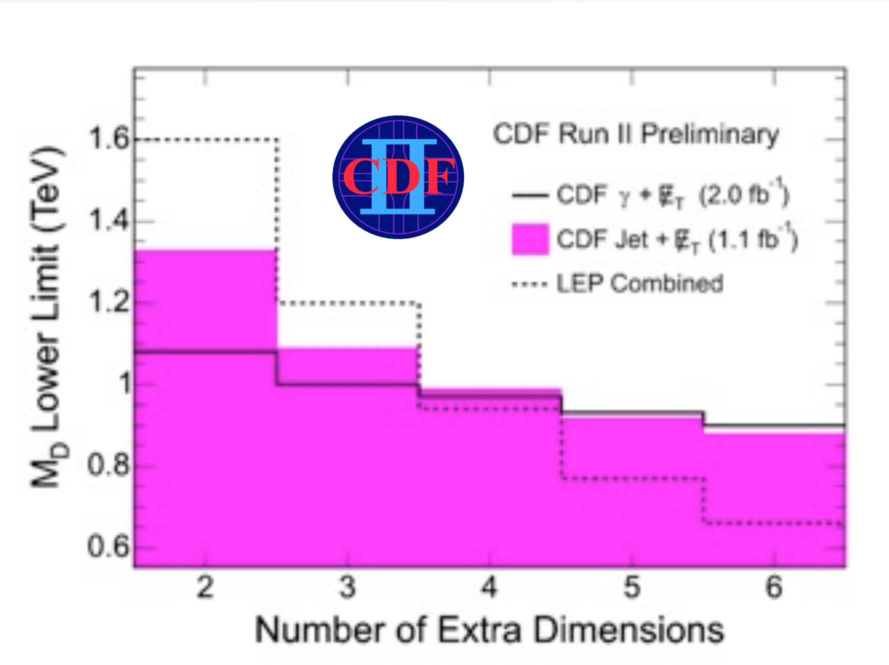
- jets + ME_T final state
- $Z(\nu\nu)$+jets is irreducible background
  - Challenging signature due to large instrumental backgrounds from jet mismeasurement, cosmics, etc.
- DØ pioneered this search and set limits [PRL, **90** 251802 (2003)] M_P > 1.0-0.6 TeV for n=2…7
- CDF analysis based on 1.1 fb^{-1}
  - Central jet w/ E_T > 150 GeV
  - ME_T > 120 GeV
  - No other jets w/ E_T > 60 GeV
  - 779 events observed with 819 ± 71 expected (half comes from $Z(\nu\nu)$+j)
  - Set limits on the fundamental Planck scale between 0.88 and 1.33 TeV
  - Similar results with looser ME_T, E_T^j cuts

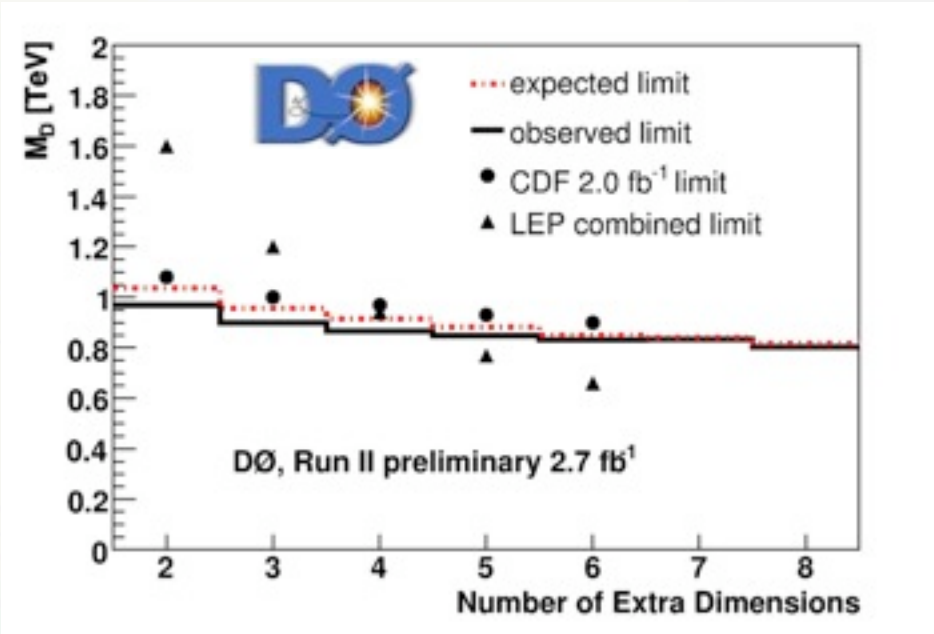




Tevatron Searches for ED in Monophotons

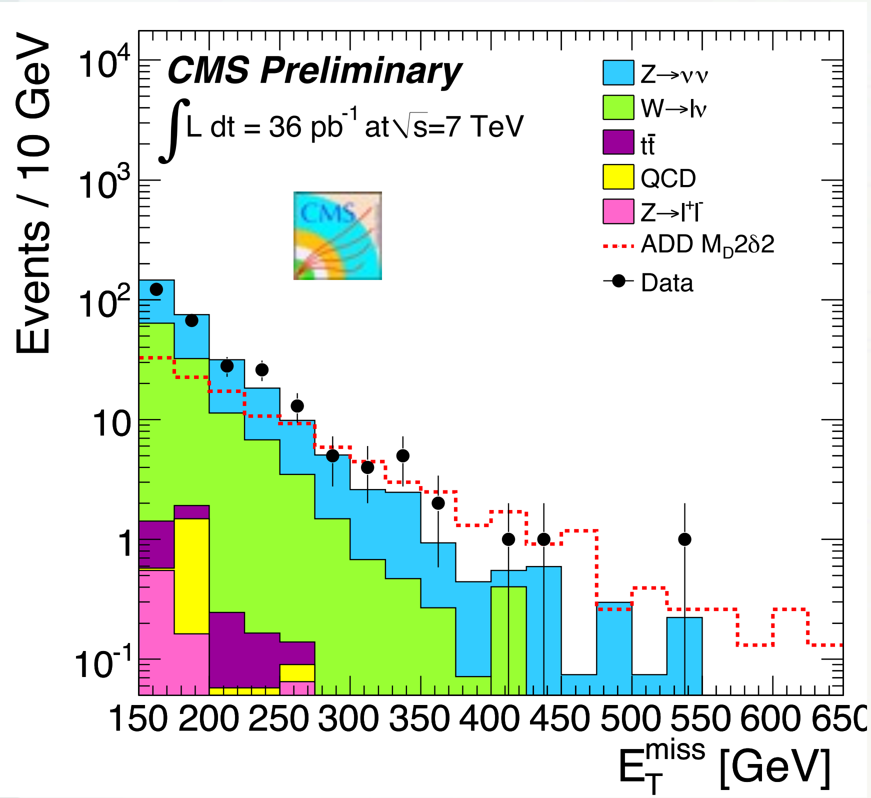
- Both CDF and DØ completed monophoton searches
- While easier than the monojet one, the sensitivity is typically not as good, especially for low number of ED
  - CDF monophoton limits approach monojet ones at large n, but require twice the luminosity

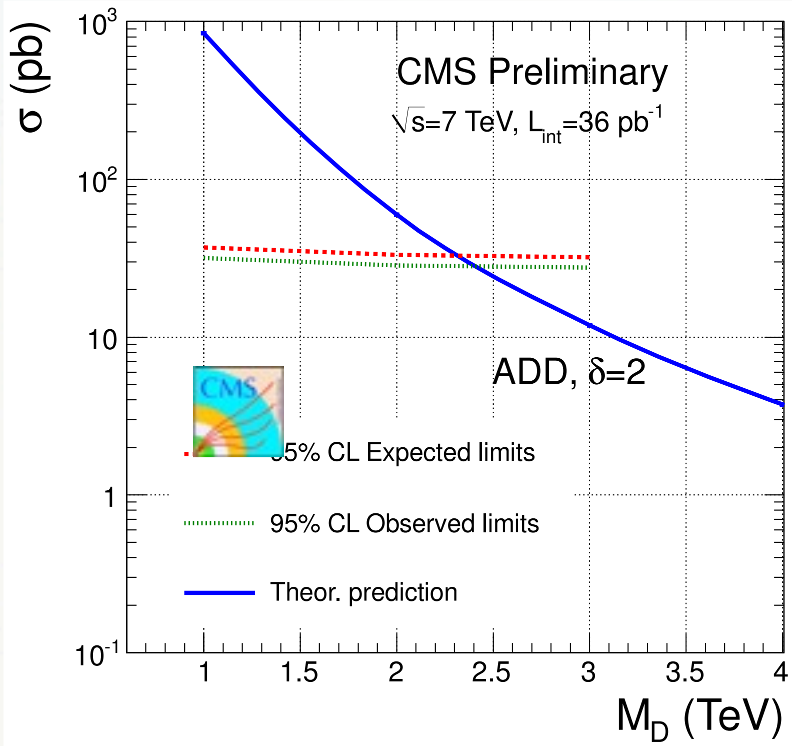




Search for Monojets at the LHC

- Jet E_T > 110 GeV (|η| < 1.7) and ME_T > 150 GeV
- Second jet veto
- Dominated by irreducible Z(νν)+jets background (determined from W (eν/μν)+jets)





CMS limits w/ 36 pb^{-1}
95% CL:
n=2 - 2.4 TeV
n=4 - 1.75 TeV

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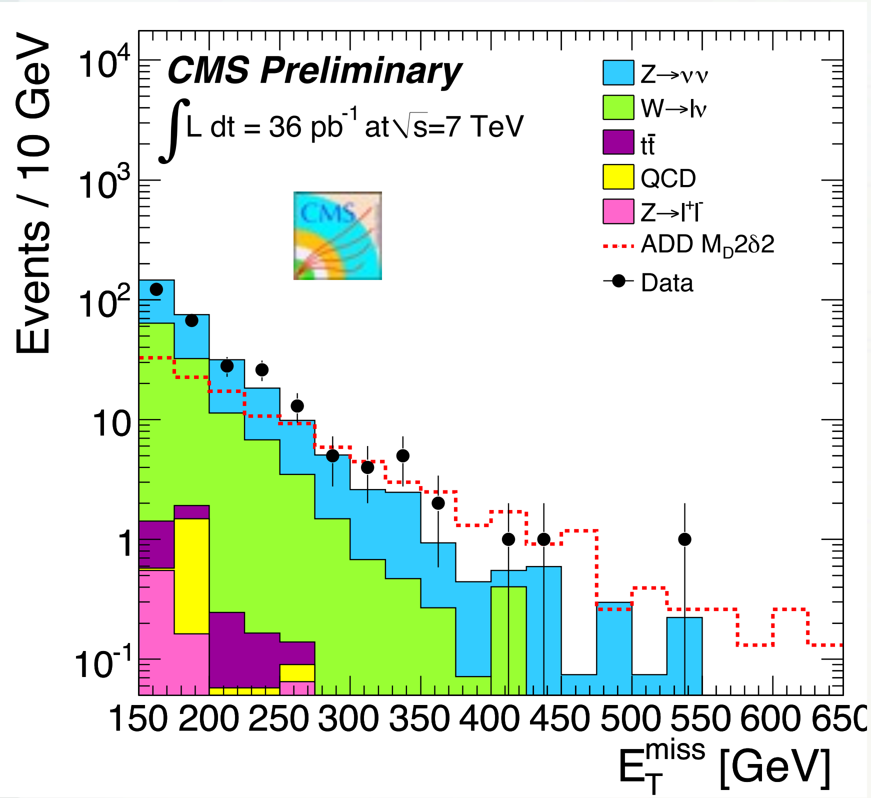

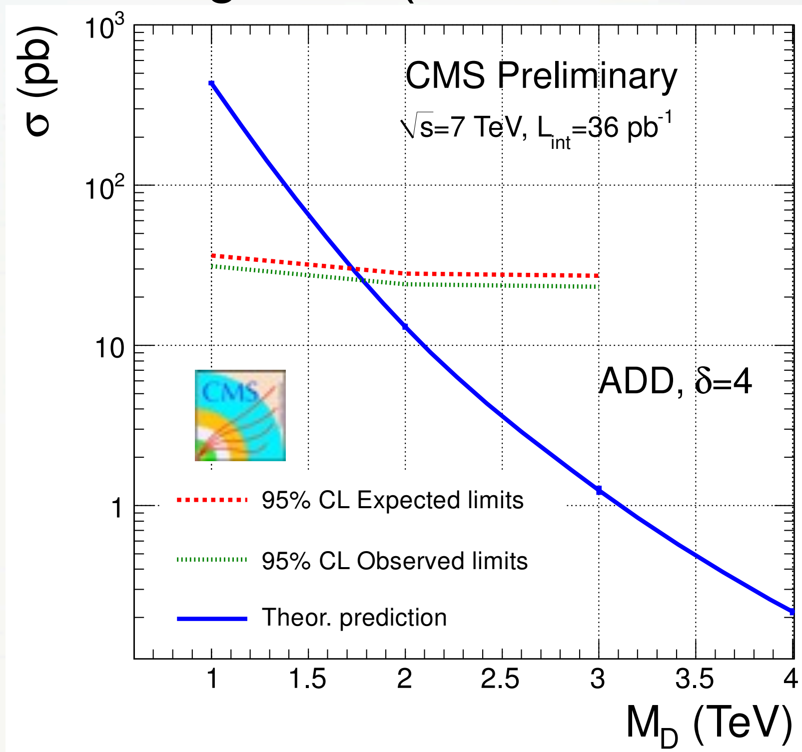

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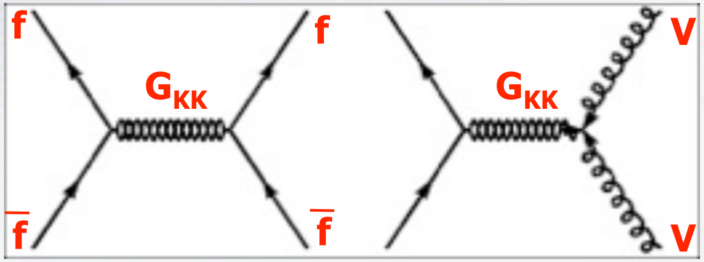
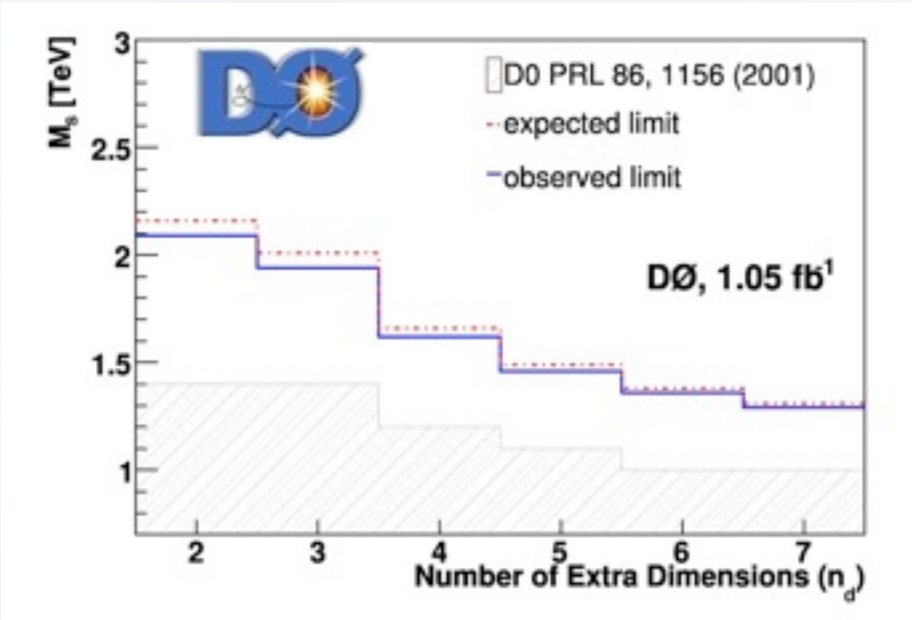
Tevatron: Virtual Graviton Effects



- Expect an interference with the SM fermion or boson pair production

$$\frac{d^2\sigma}{d\cos\theta^* dM} = \frac{d^2\sigma_{SM}}{d\cos\theta^* dM} + \frac{a(n)}{M_S^4} f_1(\cos\theta^*, M) + \frac{b(n)}{M_S^8} f_2(\cos\theta^*, M)$$

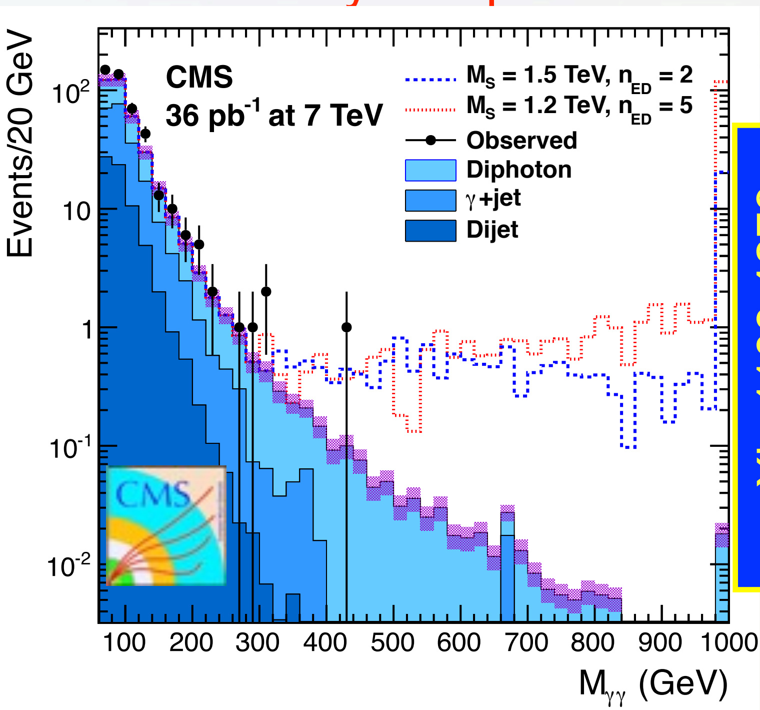


- High-mass, low $|\cos\theta^*|$ tail is a characteristic signature of LED Cheung, GL [PRD **62** 076003 (2000)]
- Best limits on the effective Planck scale come from 1 fb^{-1} DØ Run II data:
  - M_S > 1.3-2.1 TeV (n=2-7) - tightest to date
- Analysis of angular distributions in dijets yield similar sensitivity

DØ Signature	GRW [2]	HLZ [11]					
		n=2	n=3	n=4	n=5	n=6	n=7
$ee+\gamma\gamma$, 1.1 fb^{-1} [21]	1.62	2.09	1.94	1.62	1.46	1.36	1.29
Dijets, 0.7 fb^{-1} [22]	1.56		1.85	1.56	1.41	1.31	1.24

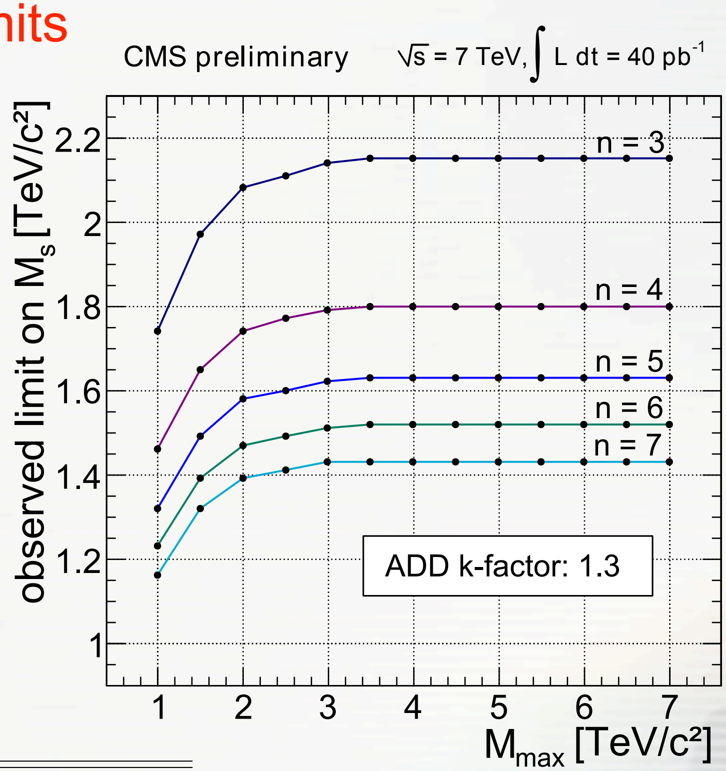
Virtual Graviton Effects at the LHC

- Clean signature, with a huge potential of a quick discovery in dimuon, dielectron, and diphoton channels:
  - Factor of ~3 gain over the Tevatron/Cosmic Ray limits in just 100 pb^{-1}
  - Will also probe generic compositeness models with similar increase in sensitivity compared to the existing limits



arXiv:1103.4279 submitted to JHEP

CMS reach for large ED in the dimuon channel



	GRW	Hewett		HLZ					
		Pos.	Neg.	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
Full	1.94	1.74	1.71	1.89	2.31	1.94	1.76	1.63	1.55
Trunc.	1.84	1.60	1.50	1.80	2.23	1.84	1.63	1.46	1.31

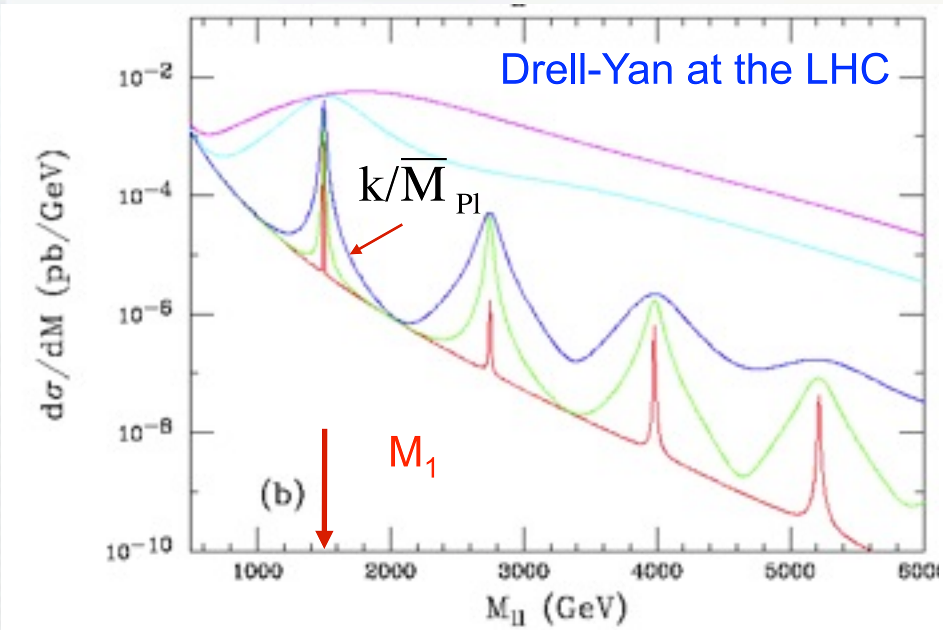
CMS reach for large ED in the diphoton channel

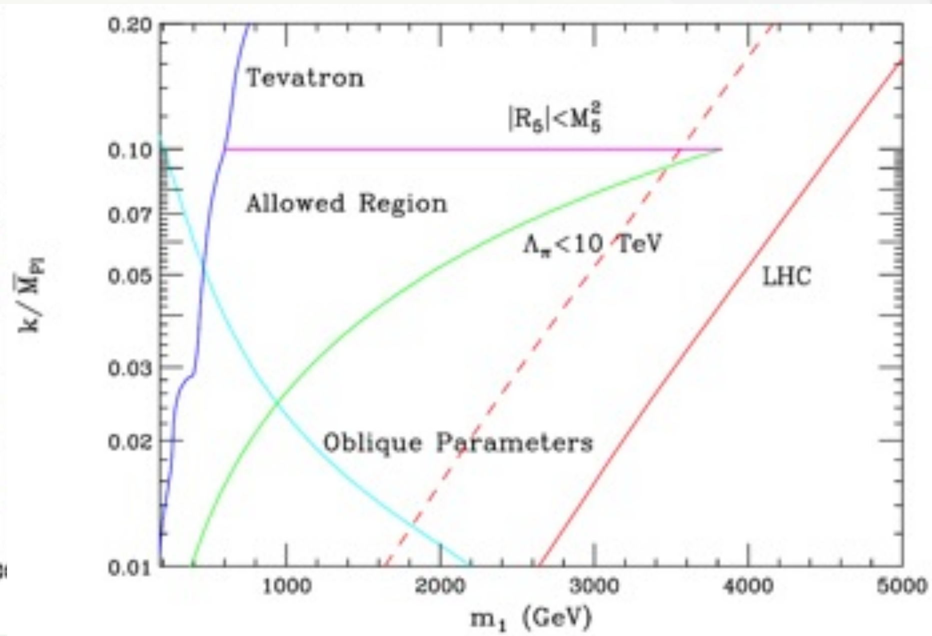
η

Randall-Sundrum Model Observables

- Need only two parameters to define the model: k and r
- Equivalent set of parameters:
  - The mass of the first KK mode, M_1
  - Dimensionless coupling $k/\overline{M}_{\rm Pl}$, which determines the graviton width

- To avoid fine-tuning and non-perturbative regime, coupling can't be too large or too small
- $0.01 \le k/\overline{M}_{\rm Pl} \le 0.10$ is the expected range
- Gravitons are narrow
- Similar observables for Z_{KK}/g_{KK} in TeV^{-1} models

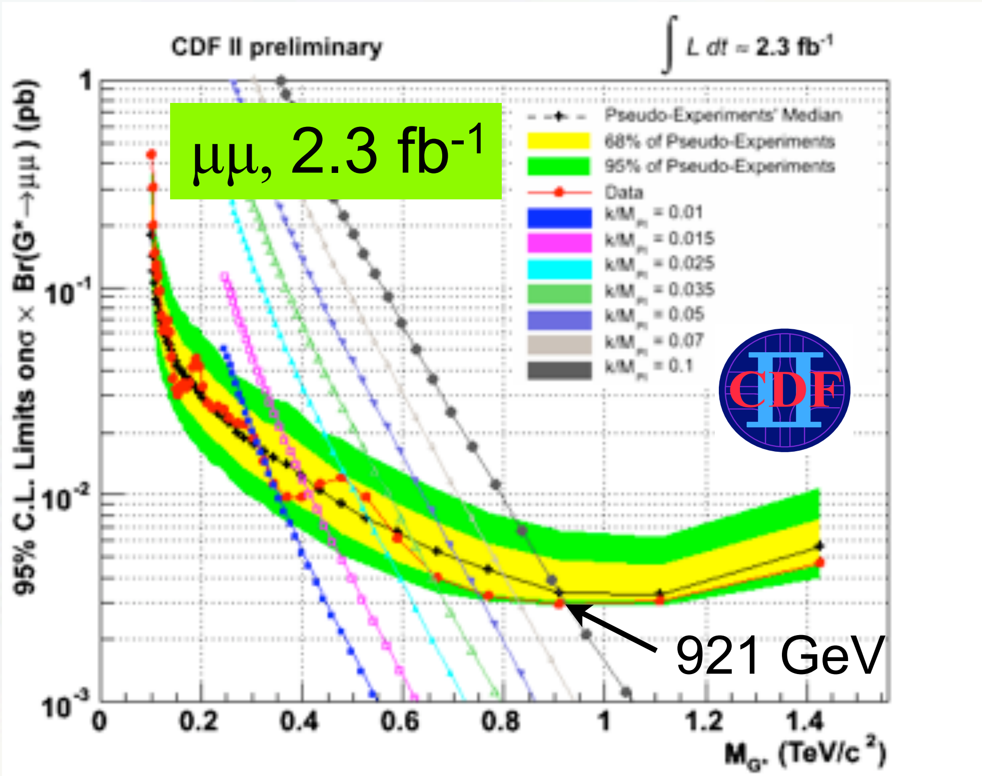


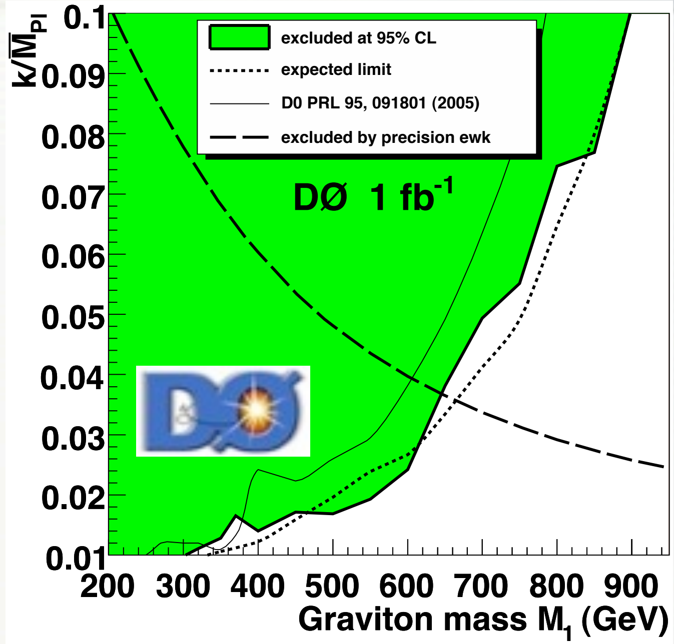


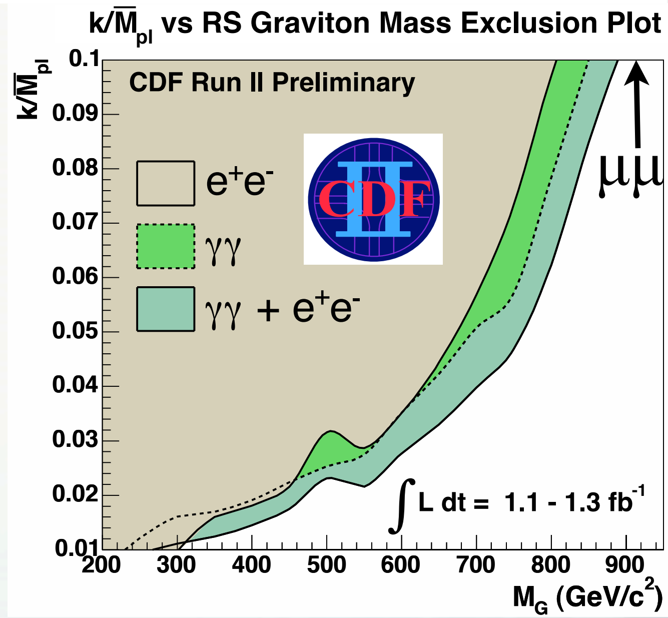
Davoudiasl, Hewett, Rizzo [PRD **63**, 075004 (2001)]

Most Recent Limits on G_{KK}

- Latest limits are 10% higher than the original ones despite 4x statistics
  - Tevatron sensitivity has really maxed out - need higher energies!

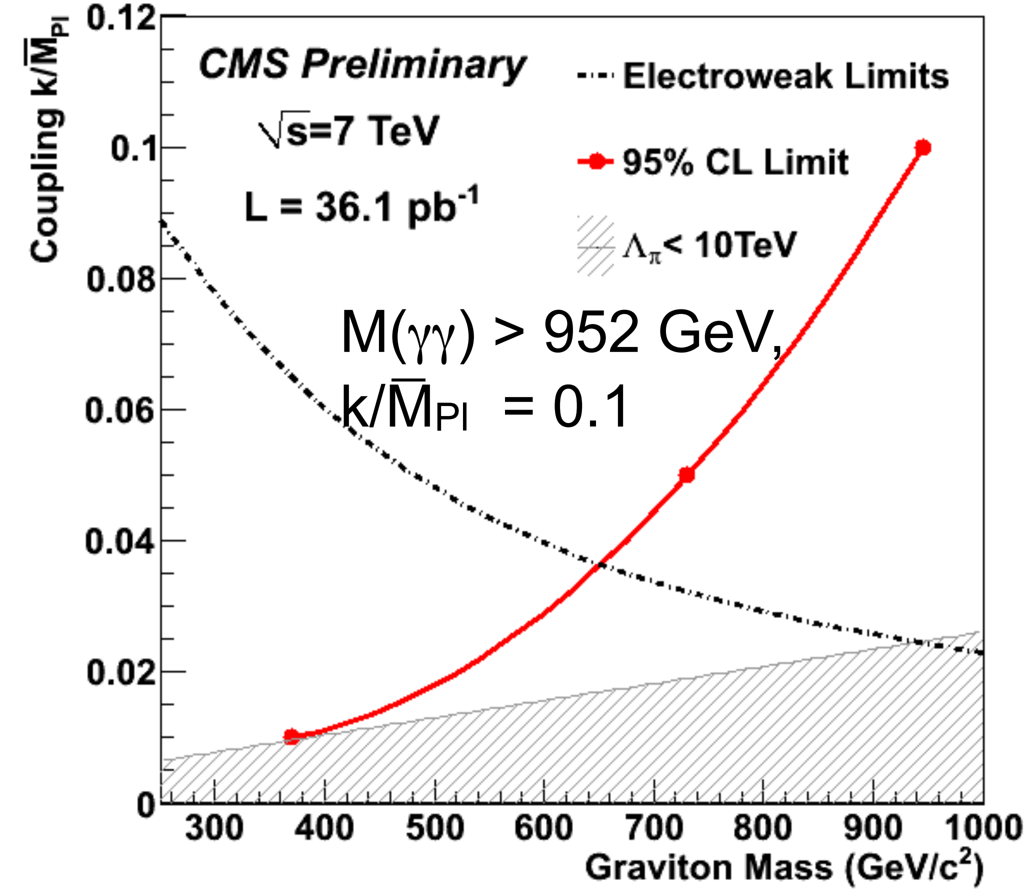




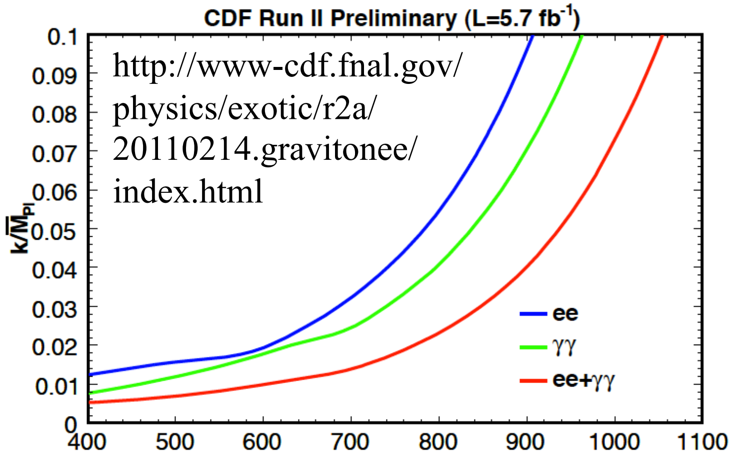


RS Gravitons at the LHC

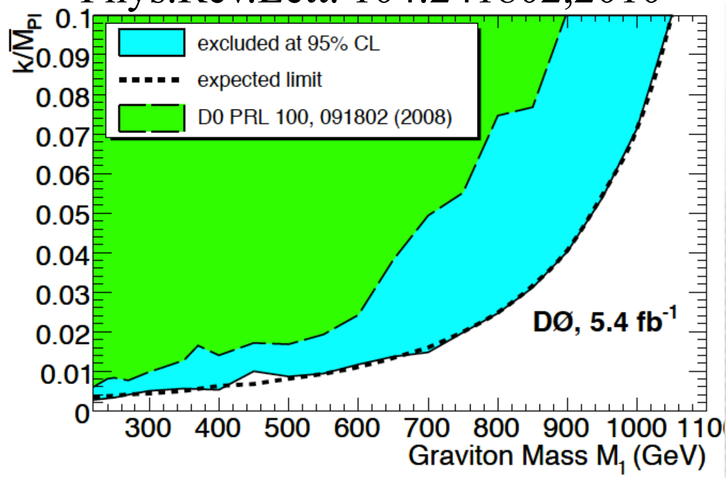
- Same analysis can be reinterpreted as search for resonances decaying into pair of photons (e.g., G_{KK})
- Just shy of the Tevatron limits (expect to exceed in combination with dileptons)



New Result from CDF



Phys.Rev.Lett. 104:241802,2010



CMS: $M(ee+\mu\mu) > 1079$ GeV, $k/\overline{M}_{Pl} = 0.1$

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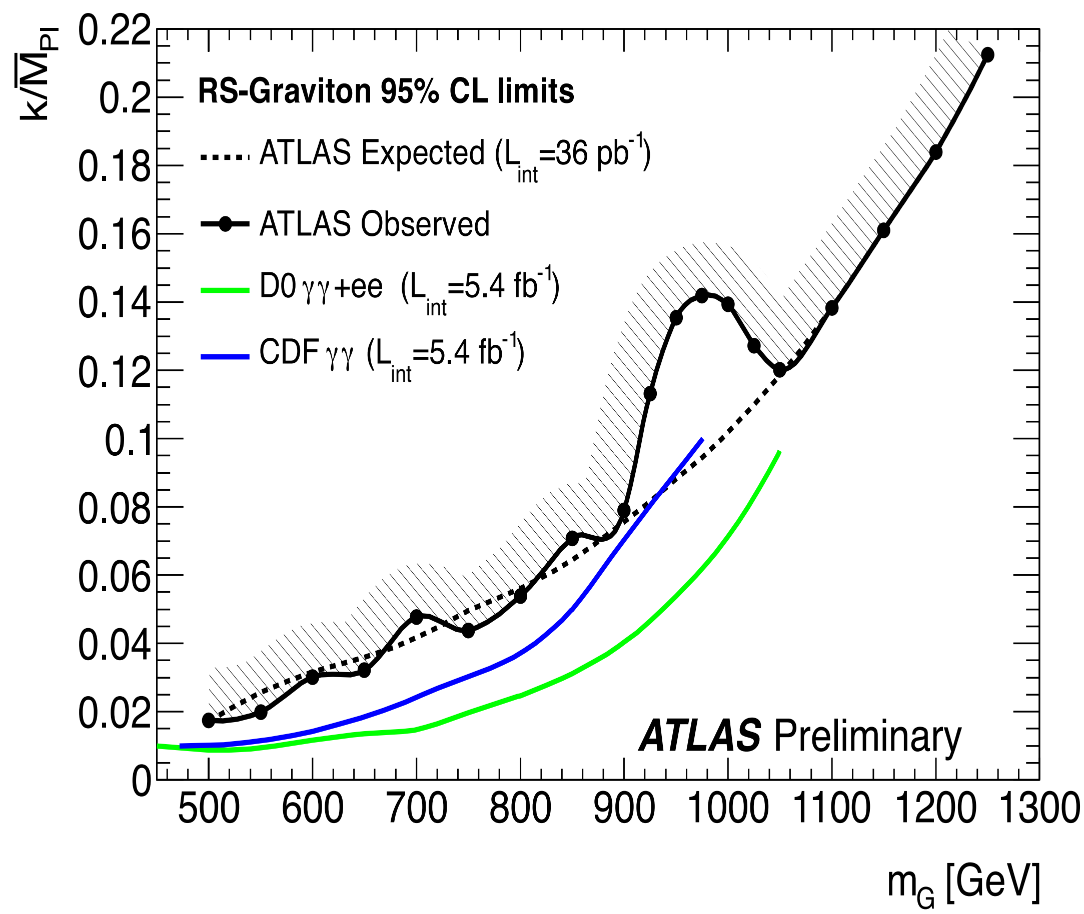

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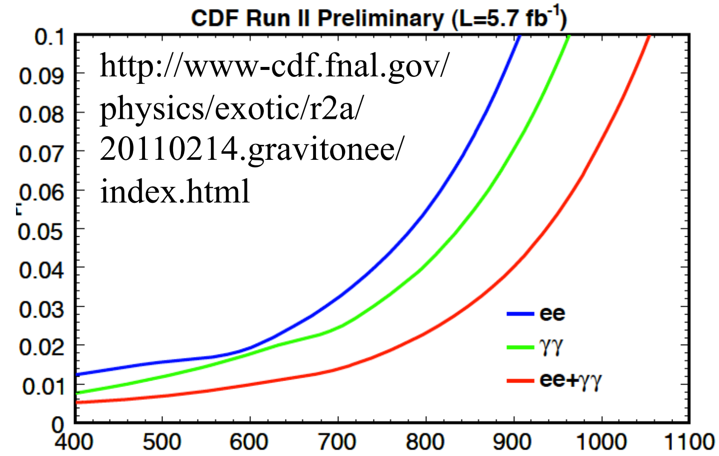

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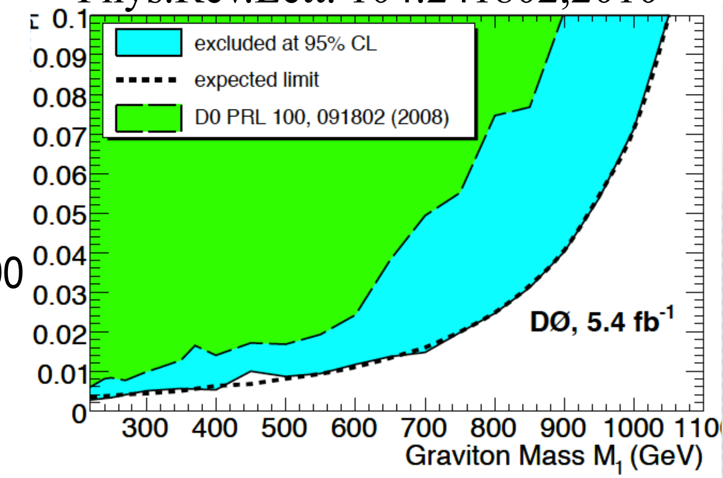

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Black Holes at the LHC?

Black Holes on Demand

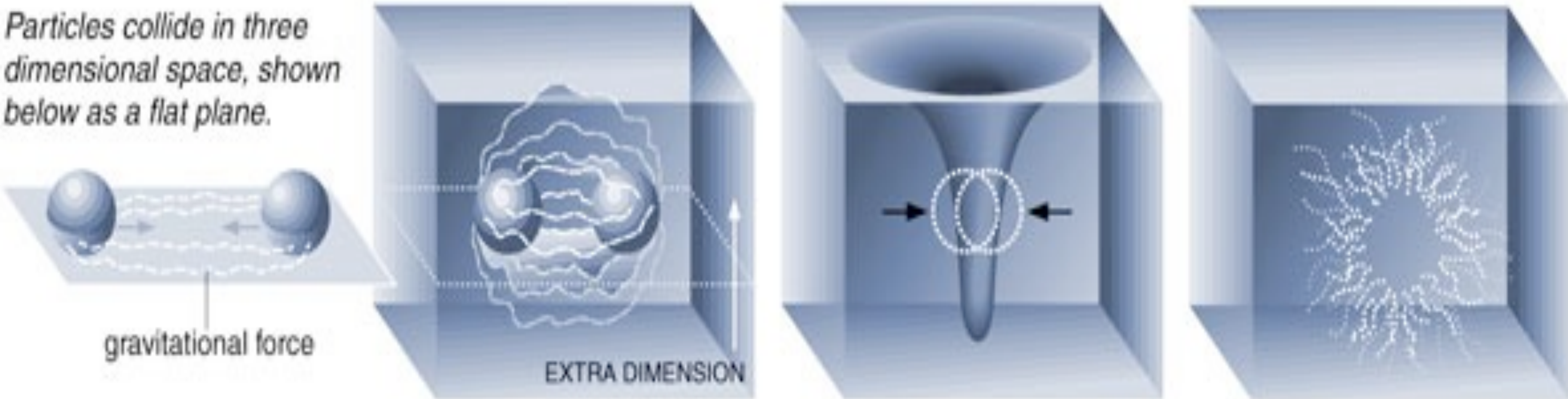
Black Holes on Demand

NYT, 9/11/01

The New York Times ON THE WEB

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

Particles collide in three dimensional space, shown below as a flat plane.



As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

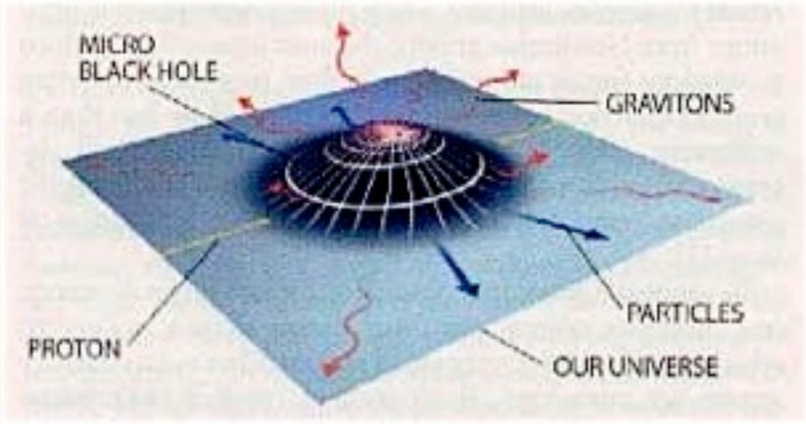
The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

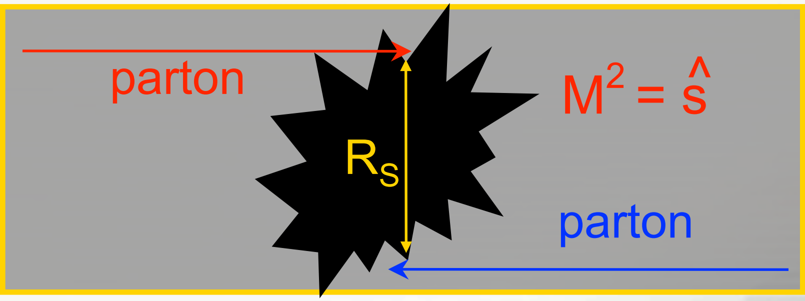
BH at LHC: Theoretical Framework

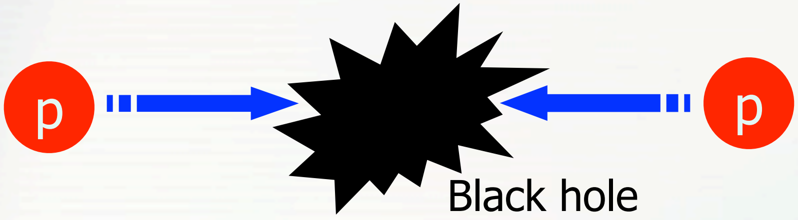
- Based on the work done with Dimopoulos a few years ago [PRL **87**, 161602 (2001)] and a related study by Giddings/Thomas [PRD **65,** 056010 (2002)]
- Extends previous, more theoretical studies by Argyres/Dimopoulos/March-Russell [PL **B441**, 96 (1998)], Banks/Fischler [JHEP, **9906**, 014 (1999)], Emparan/Horowitz/Myers [PRL **85**, 499 (2000)] to collider phenomenology
- Big surprise: BH production is not an exotic remote possibility, but the dominant effect!
- Main idea: when the c.o.m. energy reaches the fundamental Planck scale, a BH is formed!
- Also true in the RS models where Λ_π is the characteristic scale

Artist's view:



Cross section is given by a black disk approximation:





$\sigma \sim \pi R_S^2 \sim 1\ \text{TeV}^{-2} \sim 10^{-38}\ \text{m}^2 \sim 100\ \text{pb}$

Comparable with that of the top-quark pair production!

Assumptions and Approximations

- Fundamental limitation: our lack of knowledge of quantum gravity effects close to the Planck scale
- Consequently, no attempts for partial improvement of the results, e.g.:
  - Grey body factors
  - BH spin, charge, color hair
  - Relativistic effects and time-dependence
- Many subsequent publications studied those, but it's not really strict science due to unknown quantum gravity (QG) corrections
- The underlying assumptions rely on two simple qualitative properties:
  - The absence of small couplings;
  - The "democratic" nature of BH decays
- We expect these features to survive for light BH
- Use semi-classical approach strictly valid only for $M_{BH} \gg M_{Pl}$; only consider $M_{BH} > M_{Pl}$
- Clearly, these are important limitations, but there is no way around them without the knowledge of QG

Black Hole Production

- Schwarzschild radius is given by Argyres et al. [hep-th/9808138], after Myers/Perry [Ann. Phys. **172**, 304 (1986)]; it leads to:

$$\sigma(\hat{s} = M_{\rm BH}^2) = \pi R_S^2 = \frac{1}{M_{\rm Pl}^2}\left[\frac{M_{\rm BH}}{M_{\rm Pl}}\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{2}{n+1}}$$

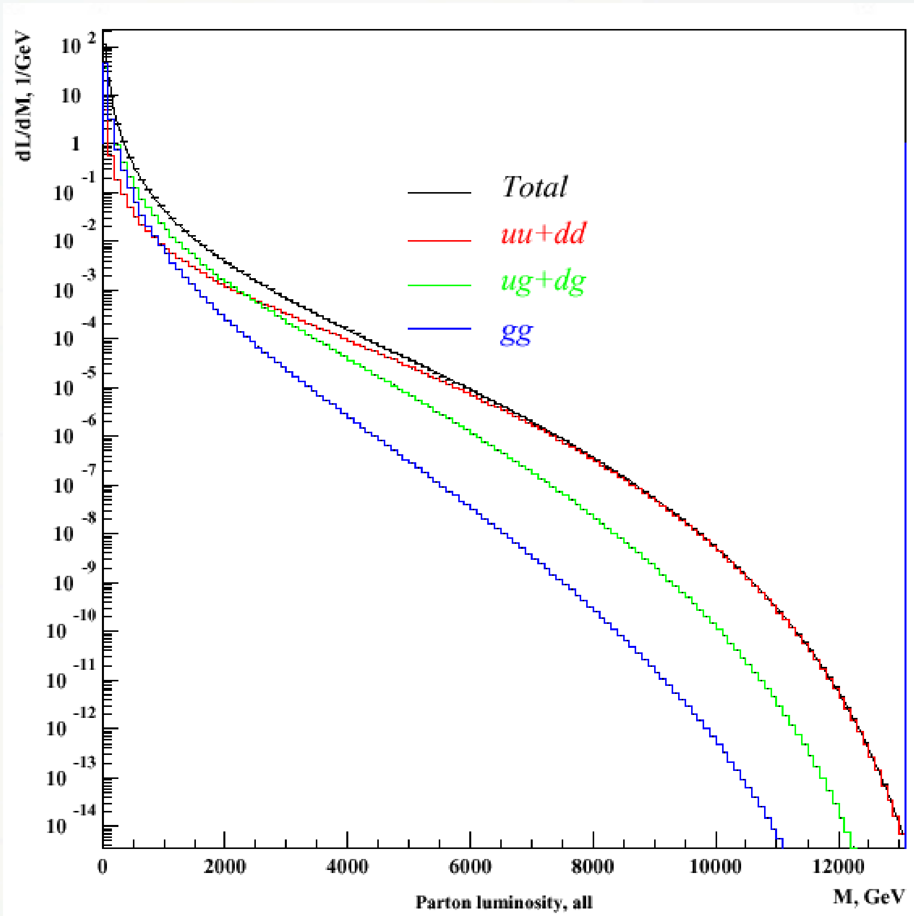
- Use parton luminosity approach with quark momentum distribution given by parton distribution functions

$$\frac{d\sigma(pp\to {\rm BH}+X)}{dM_{\rm BH}} = \frac{dL}{dM_{\rm BH}}\,\hat{\sigma}(ab\to {\rm BH})\big|_{\hat{s}=M_{\rm BH}^2}$$

$$\frac{dL}{dM_{\rm BH}} = \frac{2M_{\rm BH}}{s}\sum_{a,b}\int_{M_{\rm BH}^2/s}^{1}\frac{dx_a}{x_a}f_a(x_a)f_b\left(\frac{M_{\rm BH}^2}{sx_a}\right)$$

- Note: at c.o.m. energies ~1 TeV the dominant contribution is from quark-quark interactions (BH w/ color, B ≠ 0)

Dimopoulos, GL [PRL **87**, 161602 (2001)]



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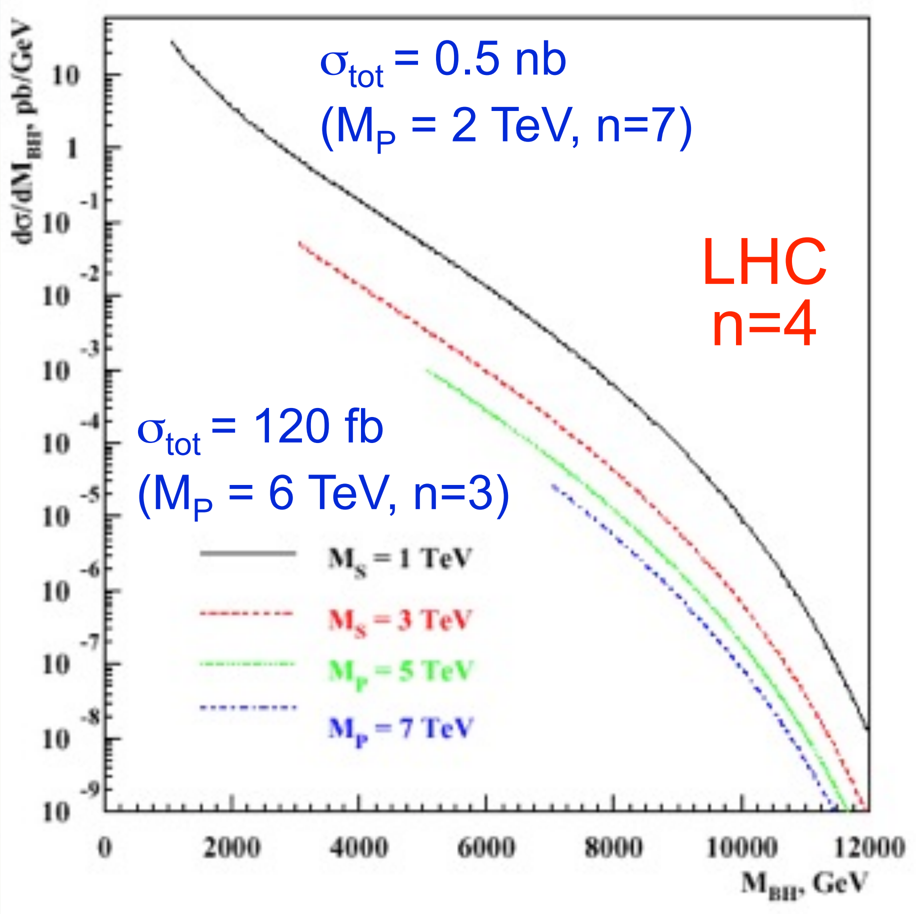
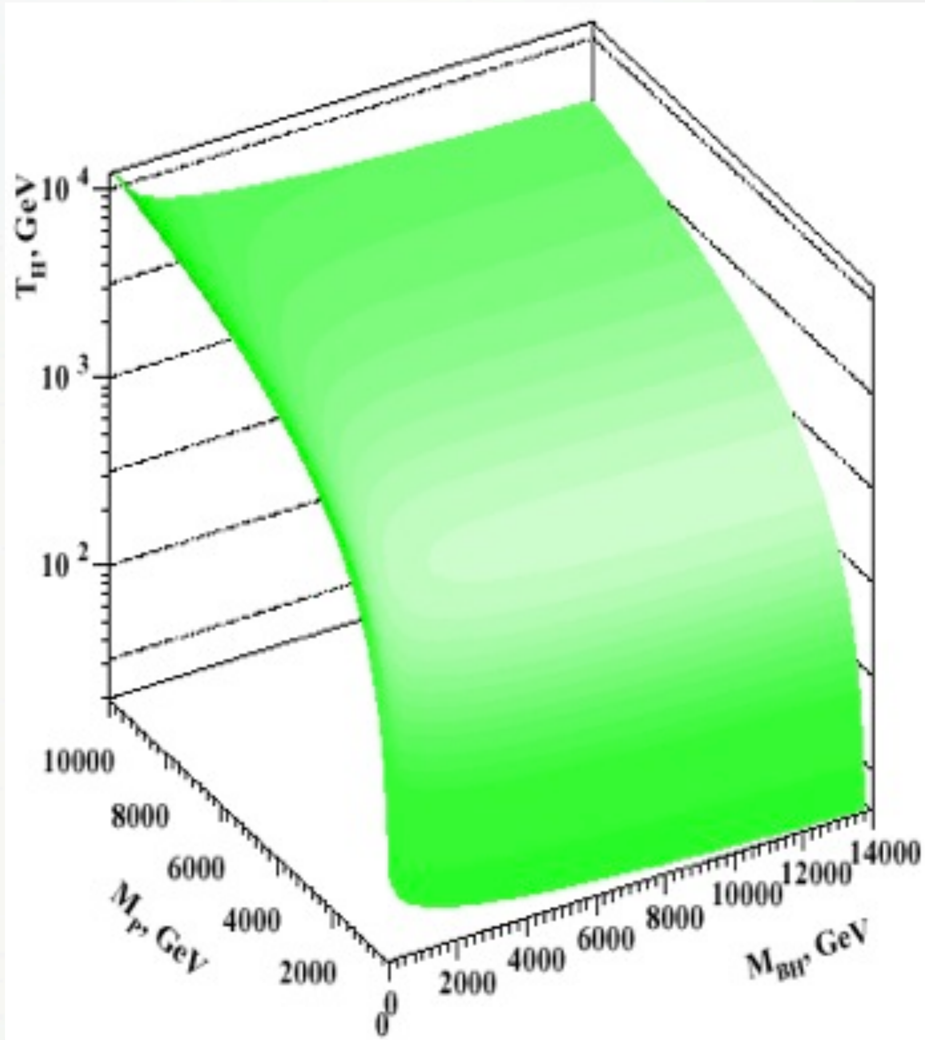


Black Hole Decay

- Hawking temperature: $R_S T_H = (n+1)/4\pi$ (in natural units $\hbar = c = k = 1$)
- BH radiates mainly in our 3D world: Emparan/Horowitz/Myers [PRL **85**, 499 (2000)]
  - $\lambda \sim 2\pi/T_H > R_S$; hence, the BH is a point radiator, producing s-waves, which depends only on the radial component
  - The decay into a particle on the brane and in the bulk is thus the same
  - Since there are much more particles on the brane, than in the bulk, decay into gravitons is largely suppressed
- Democratic couplings to ~120 SM d.o.f. yield probability of Hawking evaporation into γ, $\ell^{\pm}$, and ν ~2%, 10%, and 5% respectively
- Averaging over the BB spectrum gives average multiplicity of decay products:

$$\boxed{\langle N \rangle \approx \frac{M_{BH}}{2T_H}}$$



Stefan's law: $\tau \sim 10^{-26}$ s

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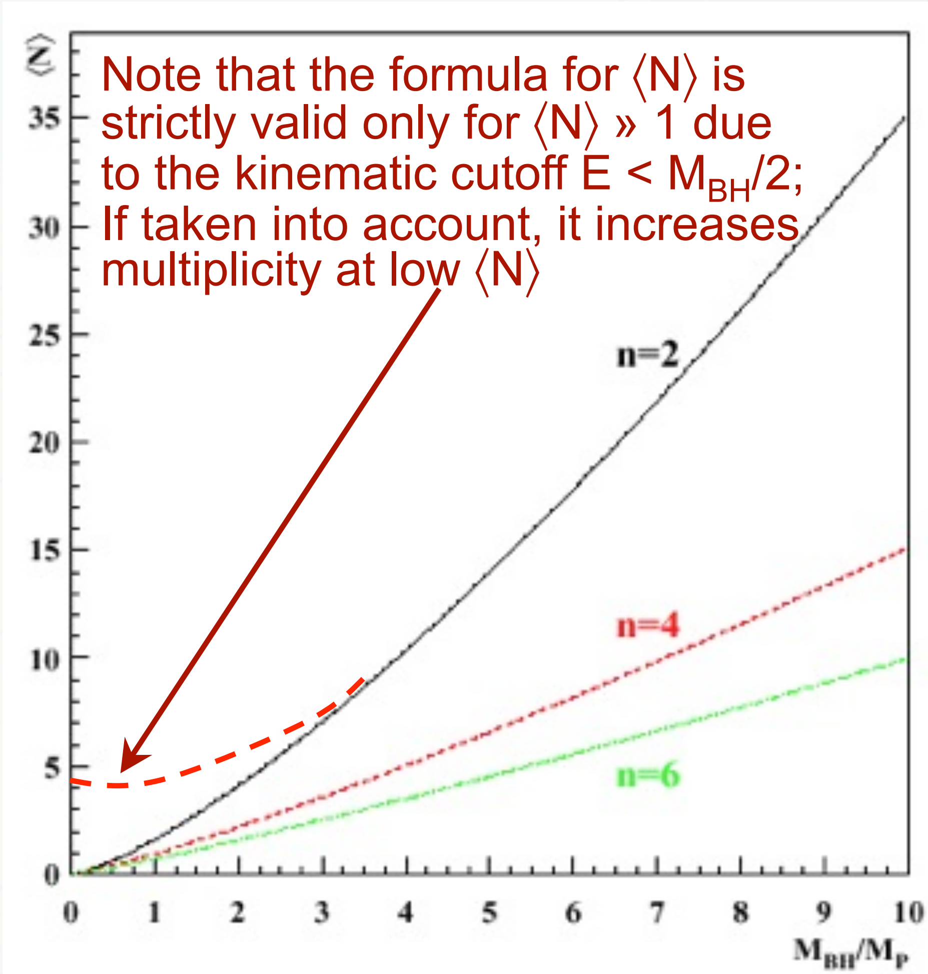

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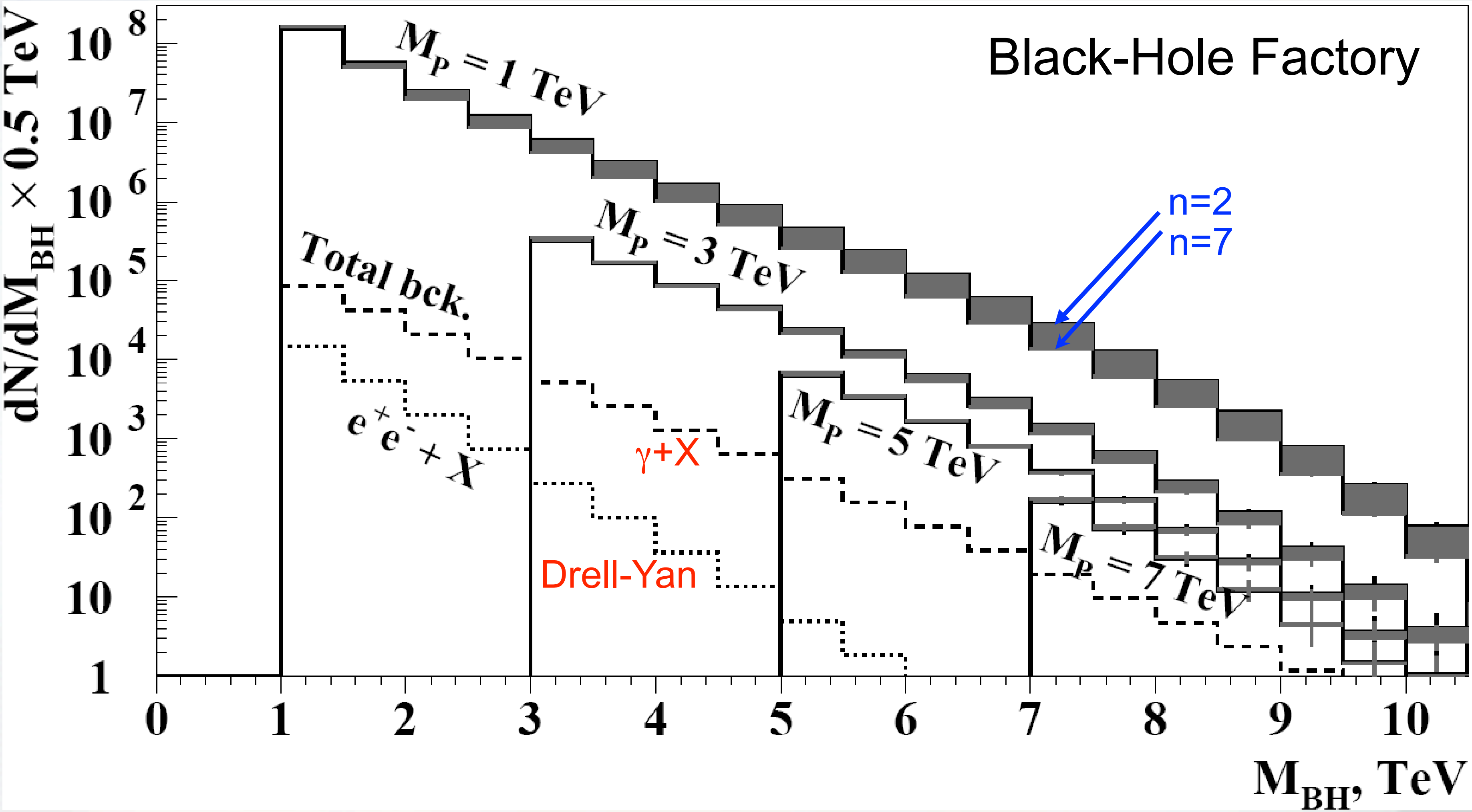
Black Hole Factory

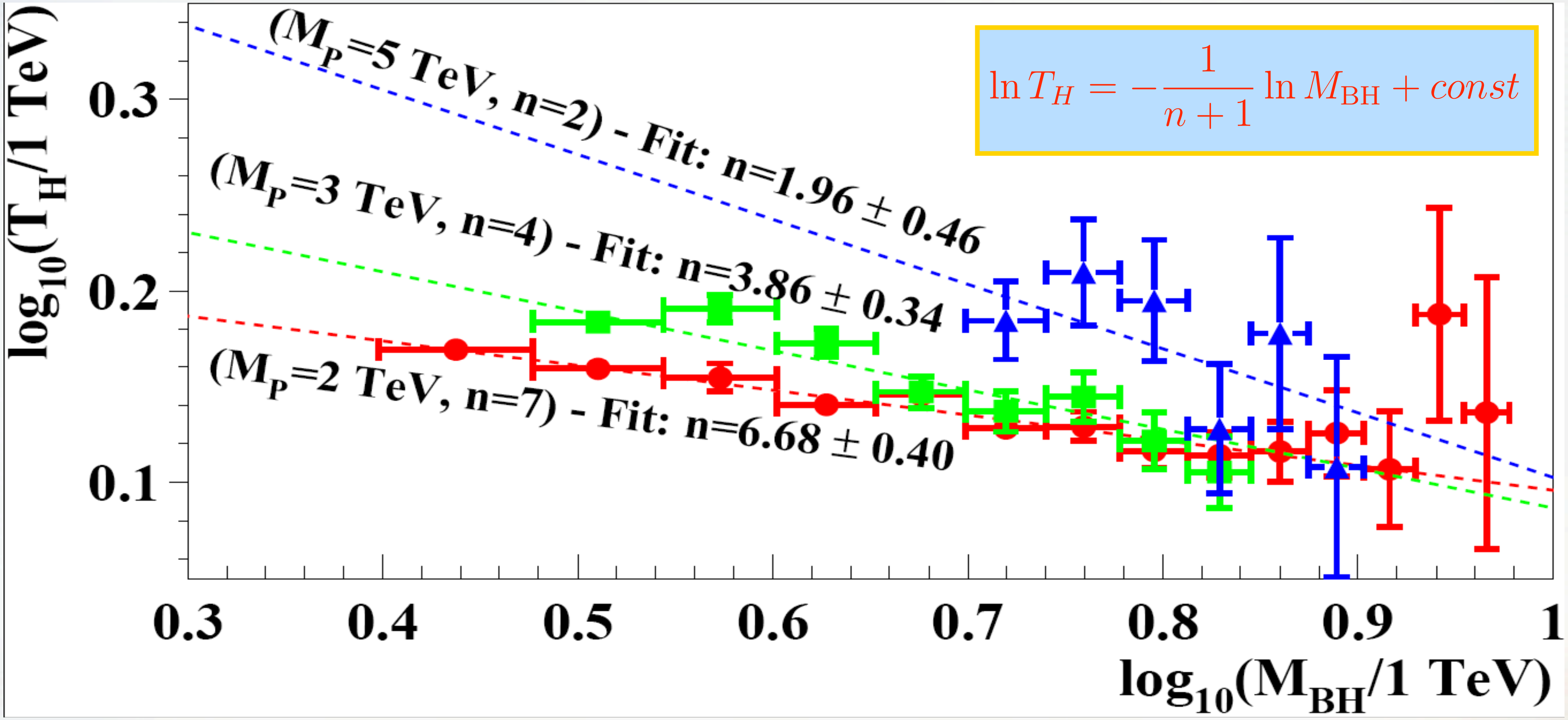
Dimopoulos, GL [PRL **87**, 161602 (2001)]



Spectrum of BH produced at the LHC with subsequent decay into final states tagged with an electron or a photon

Shape of Gravity at the LHC

Dimopoulos, GL [PRL **87**, 161602 (2001)]



- Relationship between $\log T_H$ and $\log M_{BH}$ allows to find the number of ED
  - This result is independent of their shape!
  - This approach drastically differs from analyzing other collider signatures and would constitute a "smoking cannon" signature for a TeV Planck scale

Randall-Sundrum Black Holes

- Not nearly as studied as BH in large ED
  - Originally suggested in Anchordoqui, Goldberg, Shapere [PRD **66**, 024033 (2002)]
  - A few authors extended work to various cases: Rizzo [JHEP **0501**, 28 (2005); hep-ph/0510420; hep-ph/0603242]; Stojkovic [PRL **94**, 011603 (2005)]
  - The event horizon has a pancake-like shape (squashed in the 5th dimension by $e^{-k\pi r}$)
- Nevertheless, the comparison with the ADD BH is trivial, GL [J. Phys. **G32**, R337 (2006)]
  - If $R_S e^{-k\pi r} << \pi r$ the BH is still "small" and can be treated as a 5D BH in flat space (ignoring the AdS curvature at the SM brane $\sim k^2 << 1$)
  - For BH production, Λ_π in the RS model plays the same role as the fundamental Planck scale M_D in the ADD model
  - Recent paper by Meade/Randall [arXiv:0708.3017] used a different characteristic scale: $\overline{M}_{\rm Pl} e^{-k\pi r}$, which resulted in a more conservative cross section estimate

RS to ADD Mapping

- Unlike the ADD, the 5D Planck scale, M, is of order of M_{Pl}:

$$M_{Pl}^2 = \frac{M^3}{k}\left(1 - e^{-2\pi k R_c}\right) \approx \frac{M^3}{k} \sim M^2$$

- The Schwarzschild radius: $R_S = \frac{1}{\pi M e^{-k\pi R_C}} \sqrt{\frac{M_{BH}}{3Me^{-k\pi R_C}}}$

- Given $M^3 \approx kM_{Pl}^2 = \Lambda_\pi^2 k e^{2\pi k R_C}$, $R_S = \frac{1}{\sqrt{3}\pi\Lambda_\pi}\sqrt{\frac{M_{BH}}{\tilde{k}\Lambda_\pi}} \sim \frac{1}{\Lambda_\pi}$,

  where $\tilde{k} \equiv k / \overline{M}_{Pl}$

- Compare with: $R_S^{ADD}(5D) = \frac{1}{\sqrt{\pi} M_D}\sqrt{\frac{8M_{BH}}{3M_D}}$

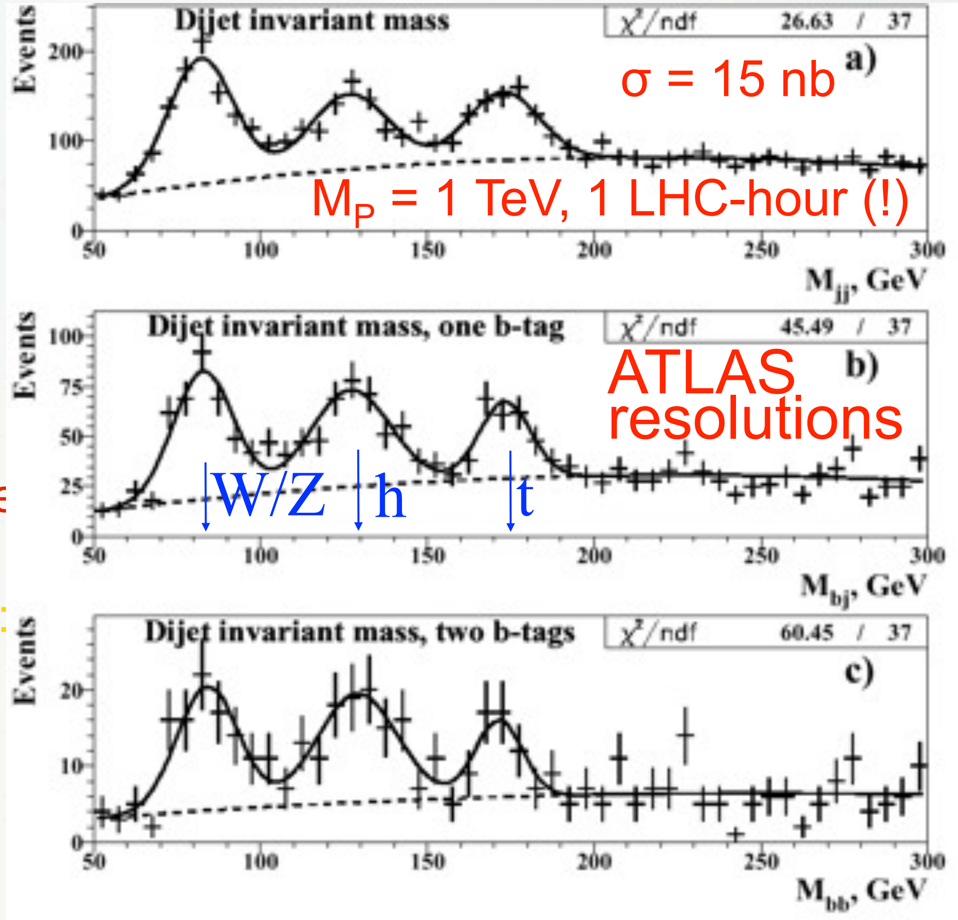
- Then if one sets $\Lambda_\pi = M_D$ and $k = 1/8\pi \approx 0.04$, the RS formula turns into the ADD one! Thus, the two cases are equivalent within the approximations we used!

- $T_H = 1/(2\pi R_S)$ (ADD formula in 5D)

New Physics in BH Decays

- Example: 130 GeV Higgs particle, which is tough to find either at the Tevatron or at the LHC
- Higgs with the mass of 130 GeV decays predominantly into a $b\bar{b}$-pair
- Tag BH events with leptons or photons, and look at the dijet invariant mass; does not even require b-tagging!
- Use a typical LHC detector response to obtain realistic results
- Time required for 5 sigma discovery:
  - M_P = 1 TeV – 1 hour
  - M_P = 2 TeV – 1 day
  - M_P = 3 TeV – 1 week
  - M_P = 4 TeV – 1 month
  - M_P = 5 TeV – 1 year
  - Standard method – 1 year w/ two calibrated detectors!

[GL, PRL **88**, 181801 (2002)]



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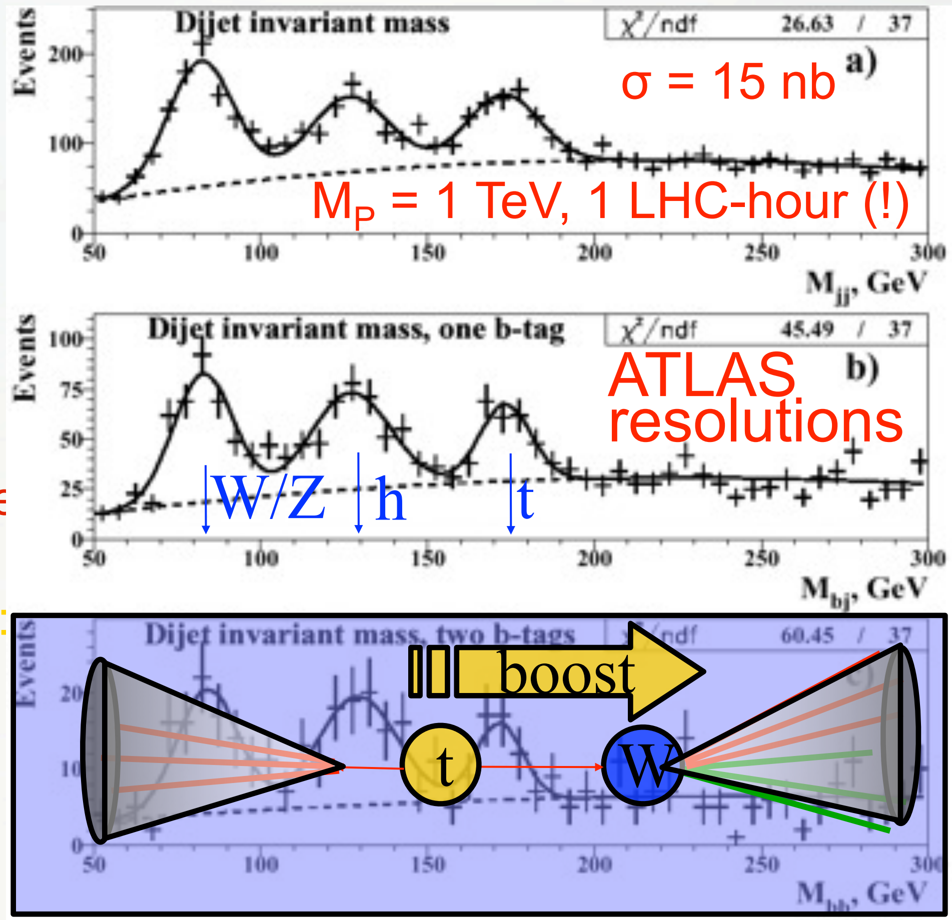

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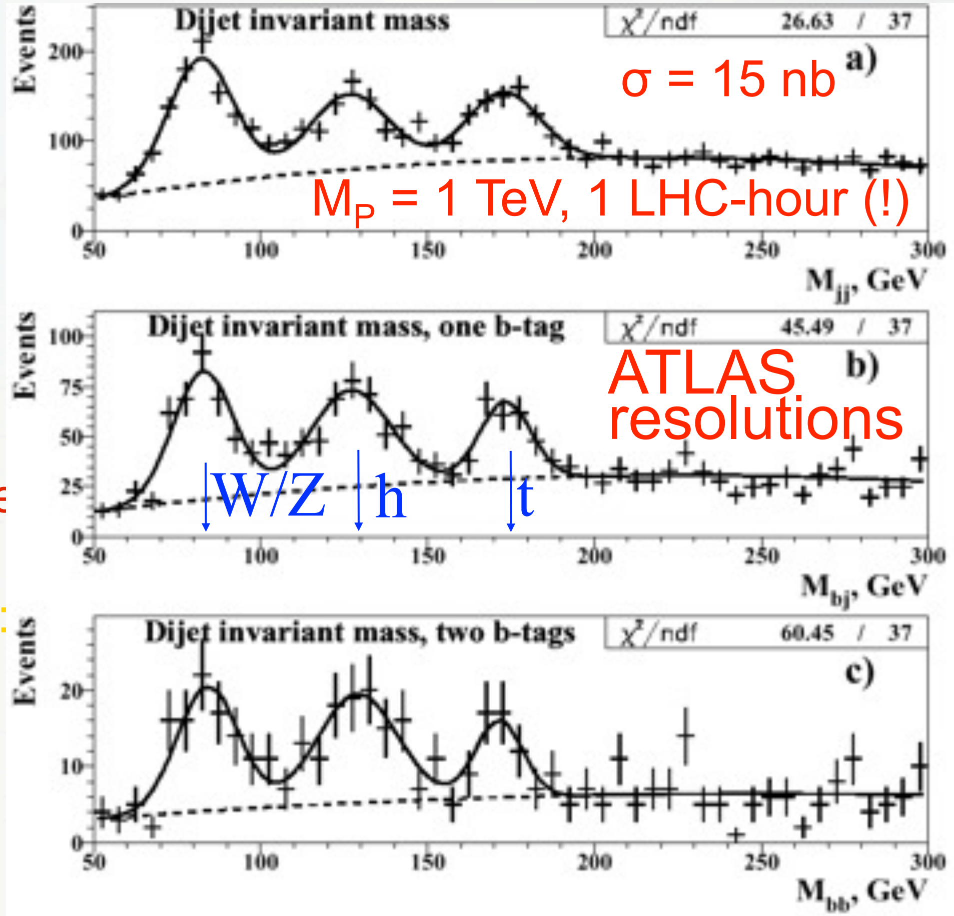
  - Standard method – 1 year w/ two calibrated detectors!

[GL, PRL **88**, 181801 (2002)]



- An exciting prospect for discovery of other new particles w/ mass ~100 GeV!

String Balls at the LHC

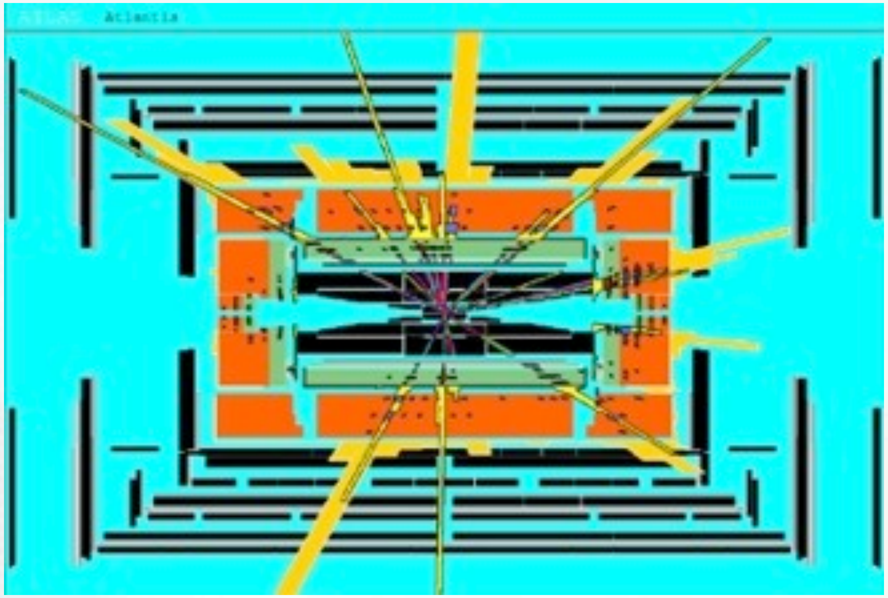
- Dimopoulos/Emparan, hep-ph/0108060 – an attempt to account for stringy behavior for $M_{BH} \sim M_S$
- GR is applicable only for $M_{BH} > M_{min} \sim M_S/g_S^2$, where g_S is the string coupling; M_P is typically less than M_{min}
- They show that for $M_S < M < M_{min}$, a *string ball*, which is a long jagged string, is formed
- Properties of a string-ball are similar to that of a BH: it evaporates at a Hagedorn temperature: $$T_H = \frac{M_S}{2\sqrt{2\pi}}$$ into a similar democratic mix of particles, with perhaps a larger bulk component
- Cross section of the string ball production is numerically similar to that of BH, due to the absence of a small coupling parameter:

$$\sigma \sim \begin{cases} \frac{g_s^2 M_{SB}^2}{M_s^4} & M_s \ll M_{SB} \le M_s/g_s\,, \\ \frac{1}{M_s^2} & M_s/g_s < M_{SB} \le M_s/g_s^2\,, \\ \frac{1}{M_P^2}\left(\frac{M_{BH}}{M_P}\right)^{\frac{2}{n+1}} & M_s/g_s^2 < M_{BH}\,. \end{cases}$$

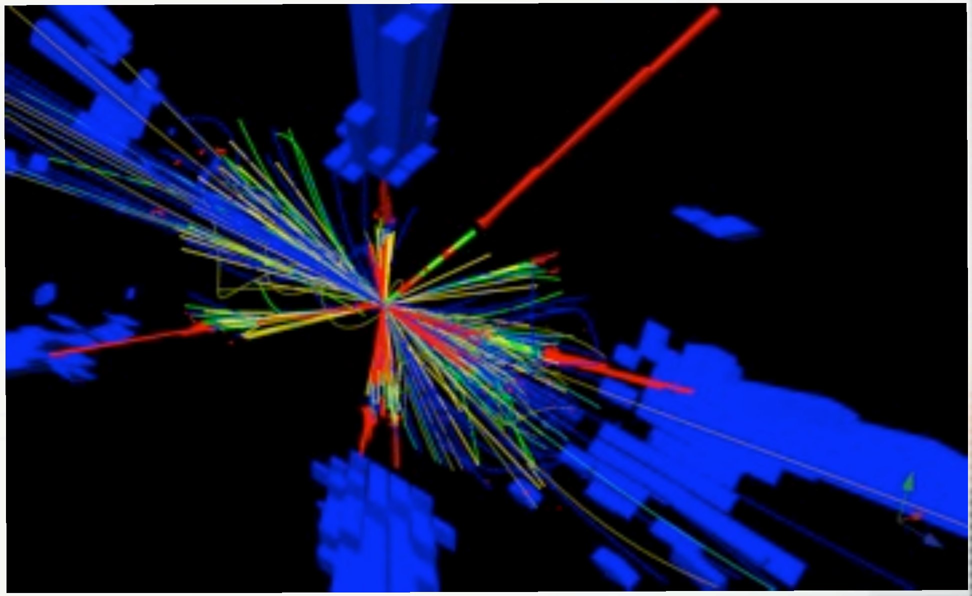
- It might be possible to distinguish between the two cases by looking at the missing energy in the events, as well as at the production cross section dependence on the total mass of the object
- Very interesting idea; more studies of that kind to come!

Black Hole Events

- Detailed studies ongoing in ATLAS and CMS
  - ATLAS – CHARYBDIS (HERWIG-based generator with an elaborated decay model by Harris/Richardson/Webber)
  - CMS – TRUENOIR (GL)/CHARYBDIS/CATFISH (Cavaglia) /BLACKMAX (Dai et al.)
  - The hunt is going on!

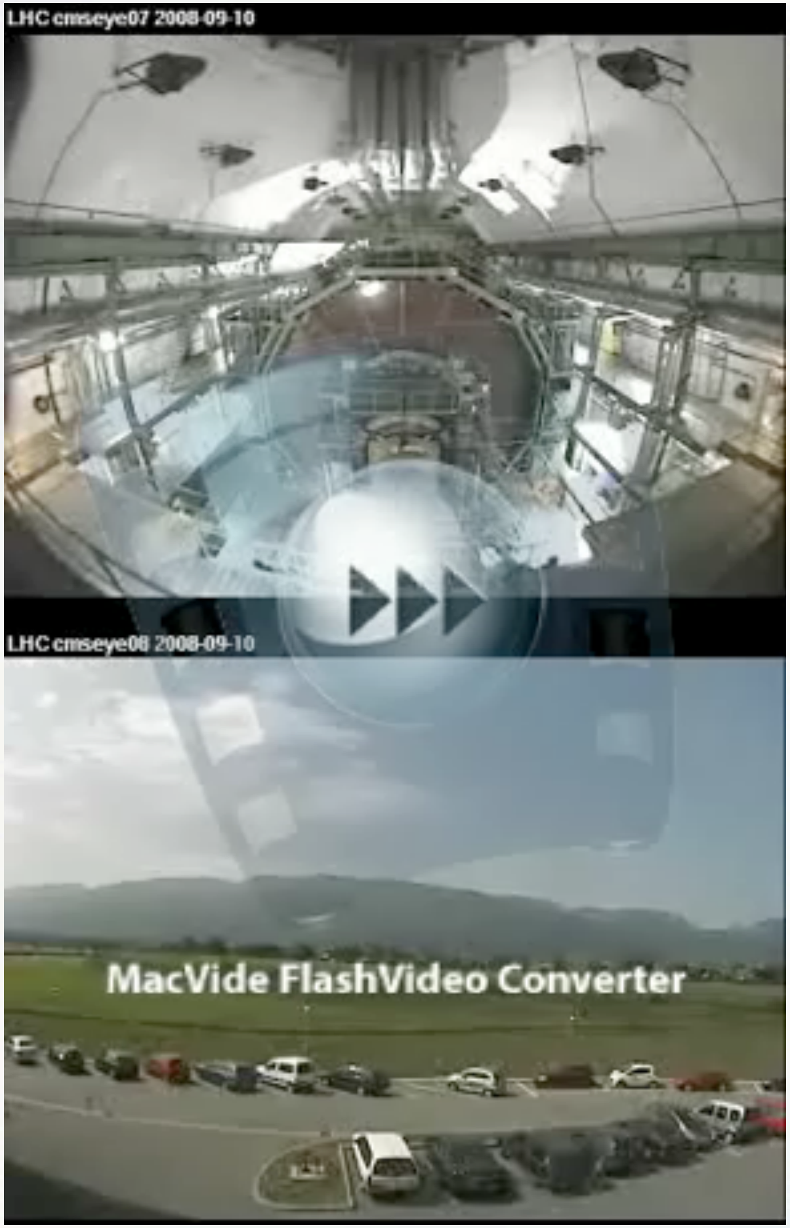


Simulated black hole event in the ATLAS detector

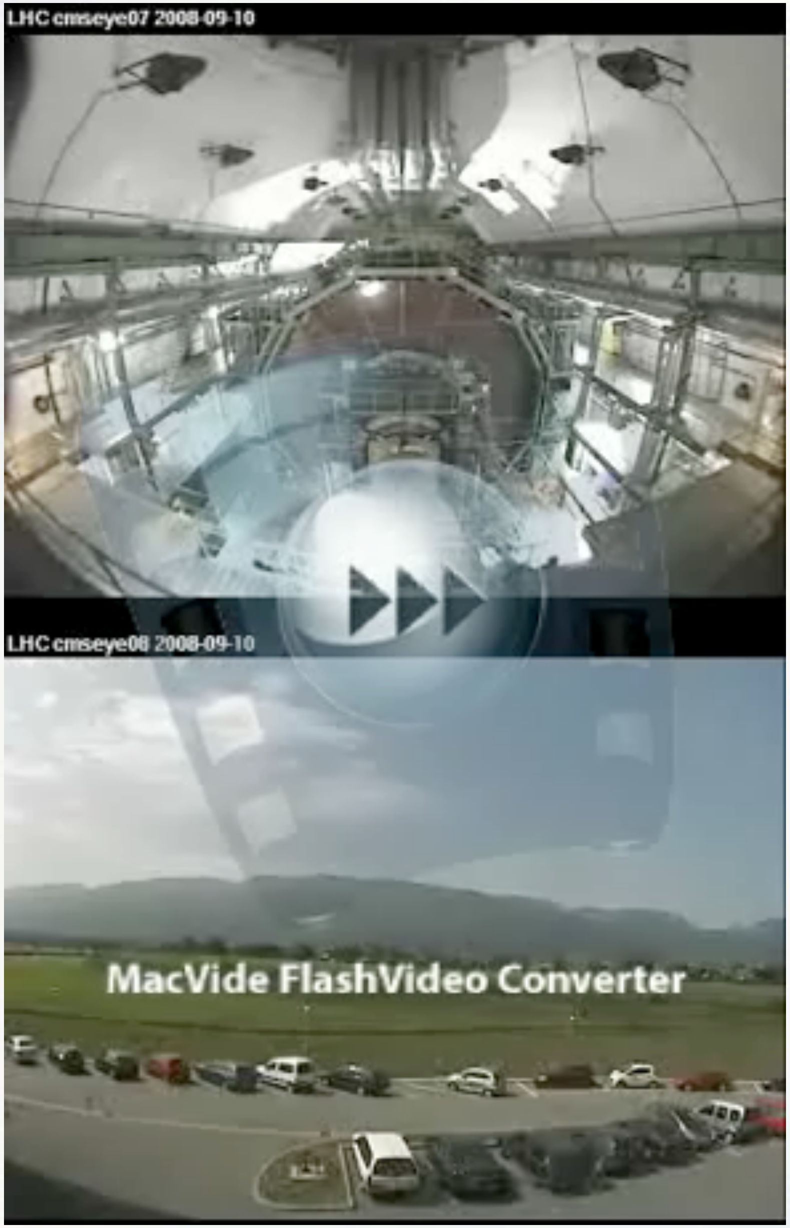


Simulated black hole event in the CMS detector

More Black Holes in CMS

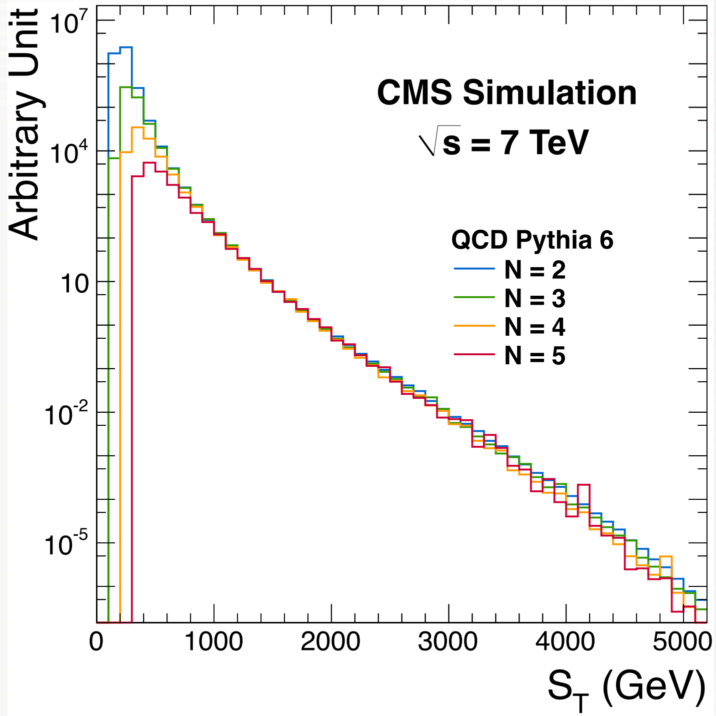


Black Holes in CMS



Black Holes in CMS

Search for Black Holes in CMS



- First dedicated collider search
- Based on $S_T = \Sigma E_T$, where the sum is over all the objects with E_T > 50 GeV, including ME_T
- Completely data-driven QCD background determination using a novel technique: S_T-invariance of the final state multiplicity
- Empirically found and tested with various MC generators (PYTHIA, ALPGEN) up to high jet multiplicity
- "Easy" to understand after the fact: FSR and ISR splitting does not change the S_T in the event appreciably due to its collinear nature
  - Nevertheless came as an initial surprise to all the theorists we mentioned it to!
  - Note that one naively would expect such scaling for the invariant mass, which is simply the sum of total energy in the detector
    - Does work as well: object minimum E_T thresholds, pile-up!

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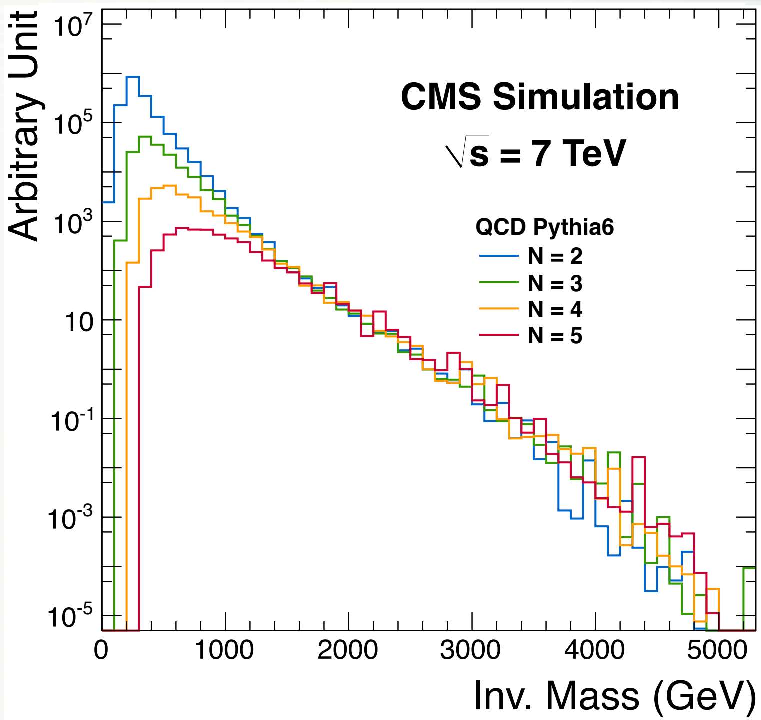

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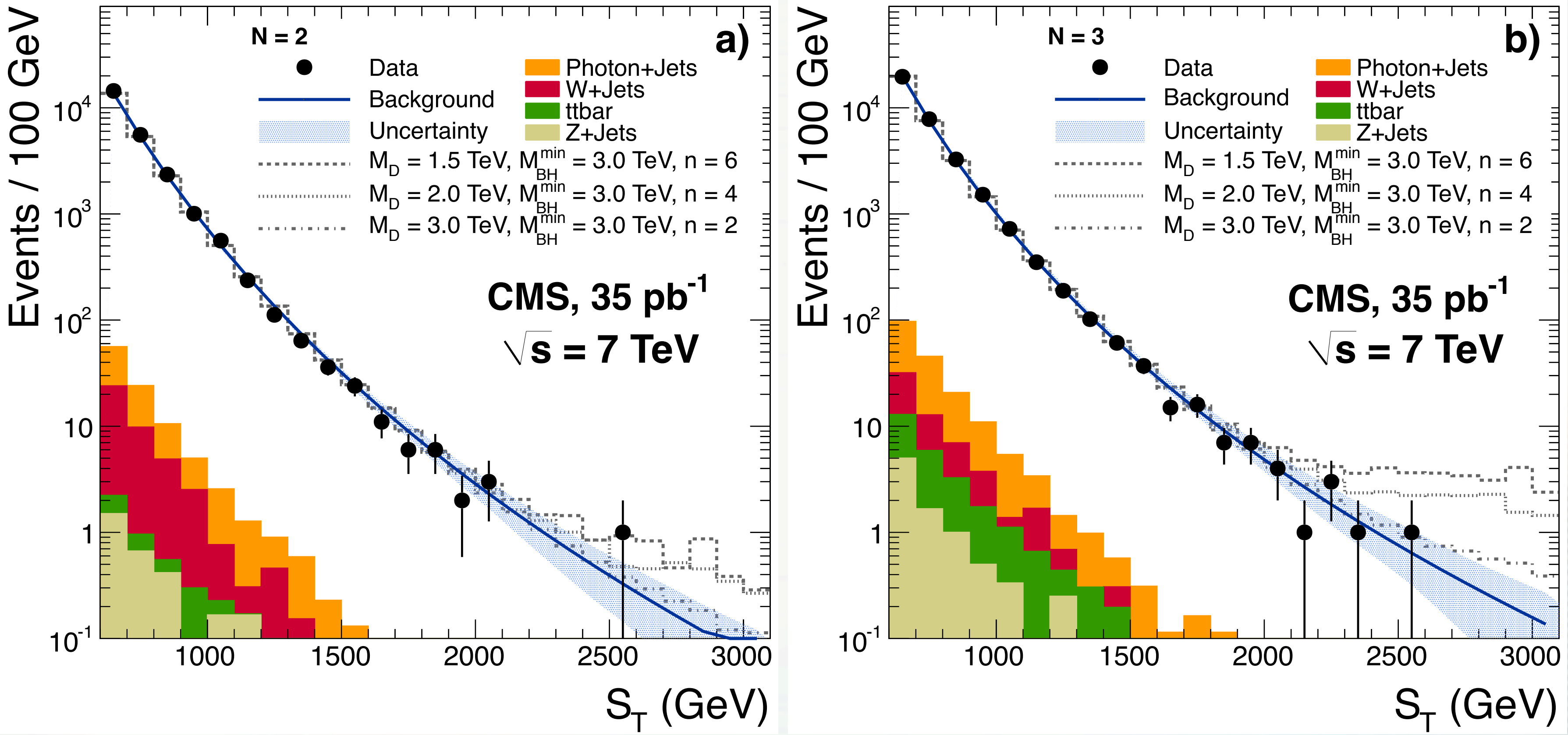
QCD Background Prediction

- Established the empirical scaling with the data, using exclusive N = 2 and 3 multiplicities
- Assign shape uncertainty due to fit parameter variation and template function choice

arXiv:1012.3375, Phys. Lett. **B697** (2011) 434



Wednesday, April 13, 2011

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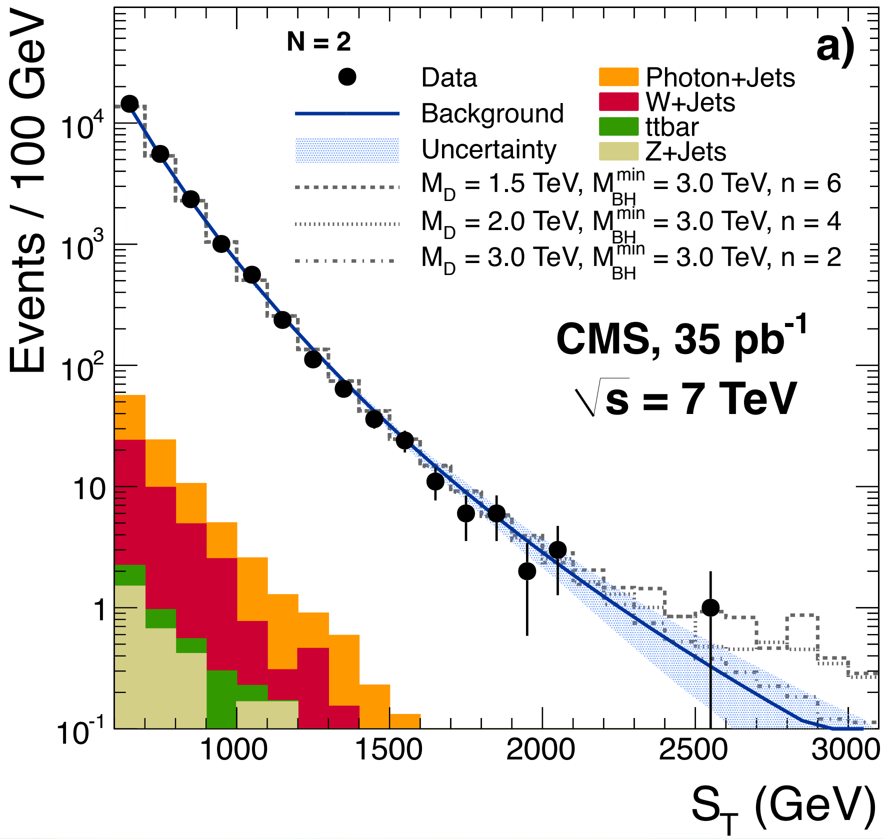
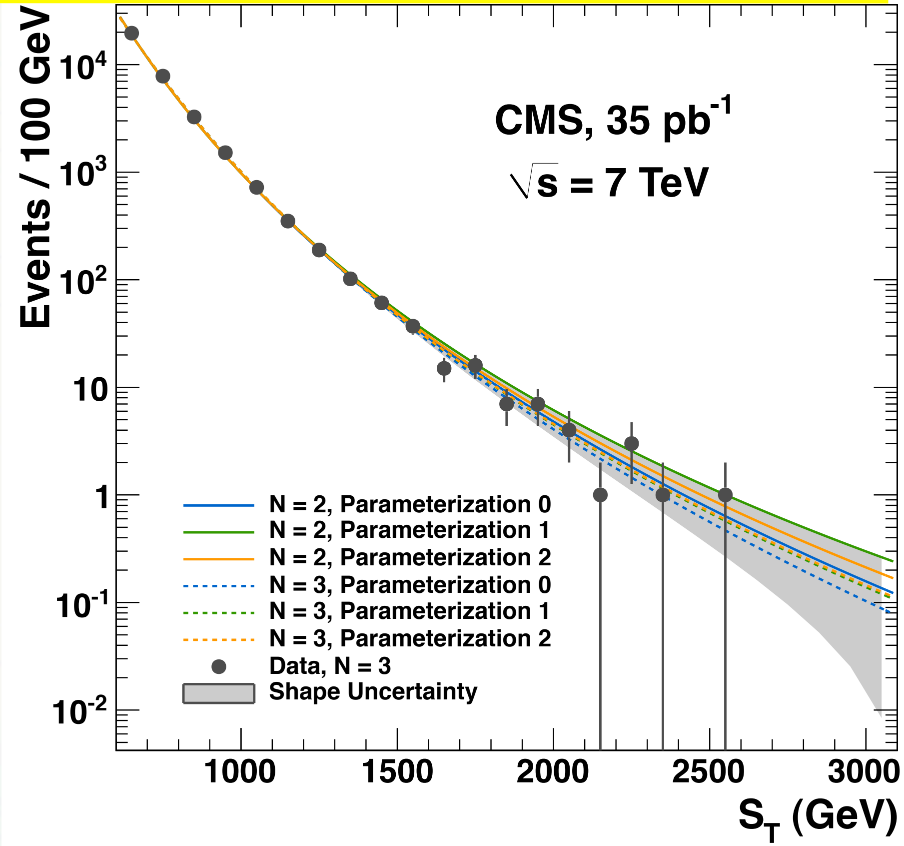
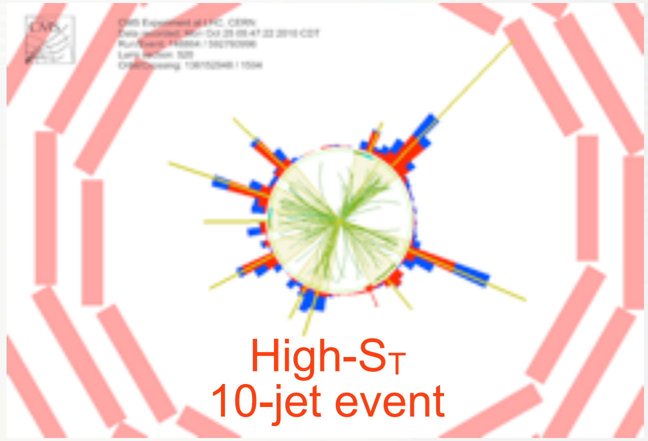




Limits on Black Holes

- Used the N=2 shape with its uncertainties, to fit higher multiplicities, where the signal is expected to be most prominent
- Given no excess, set limits on the minimum BH mass of 3.5-4.5 TeV in semi-classical approximation
- First direct limits at colliders



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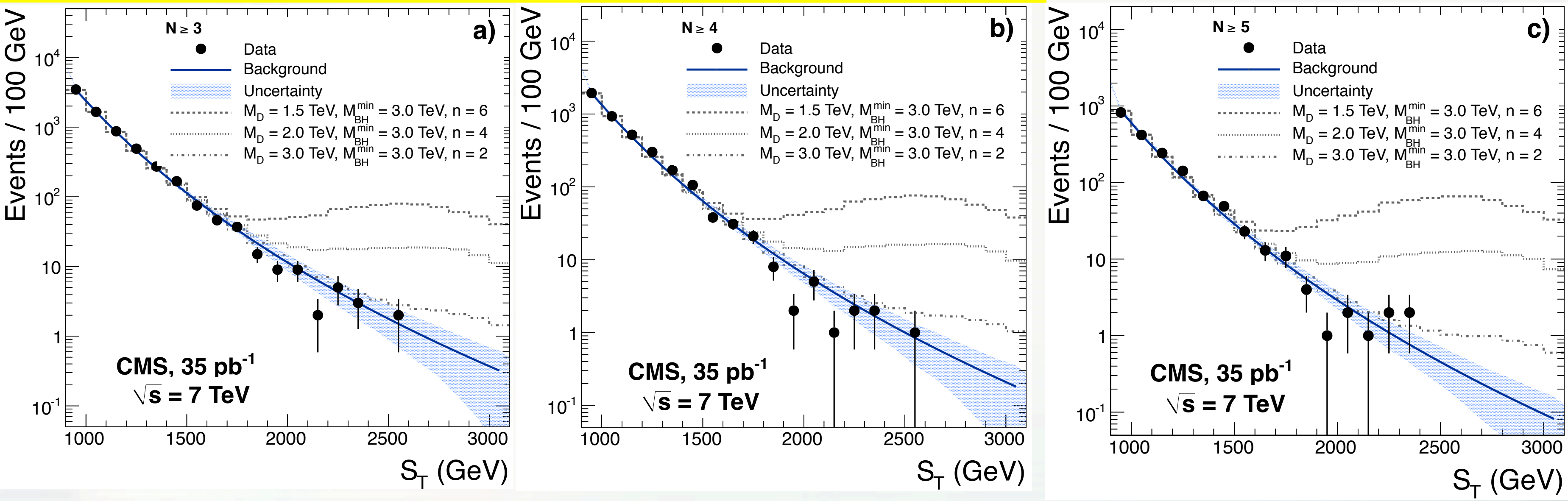

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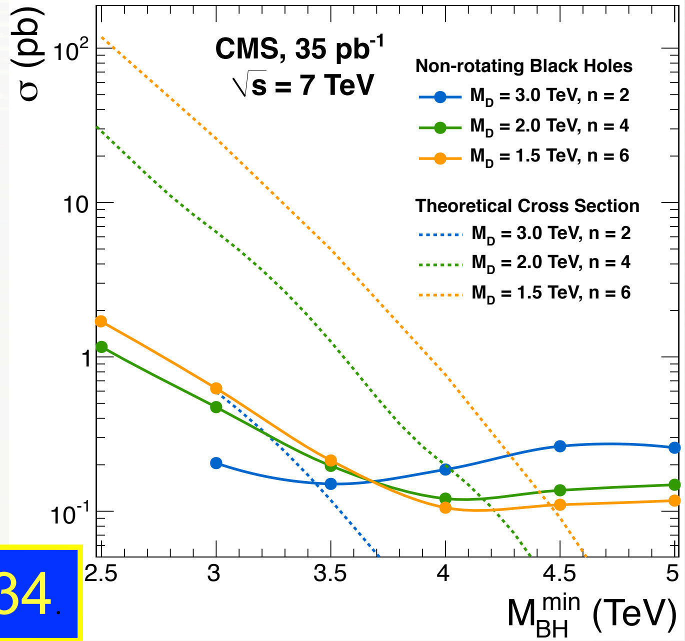

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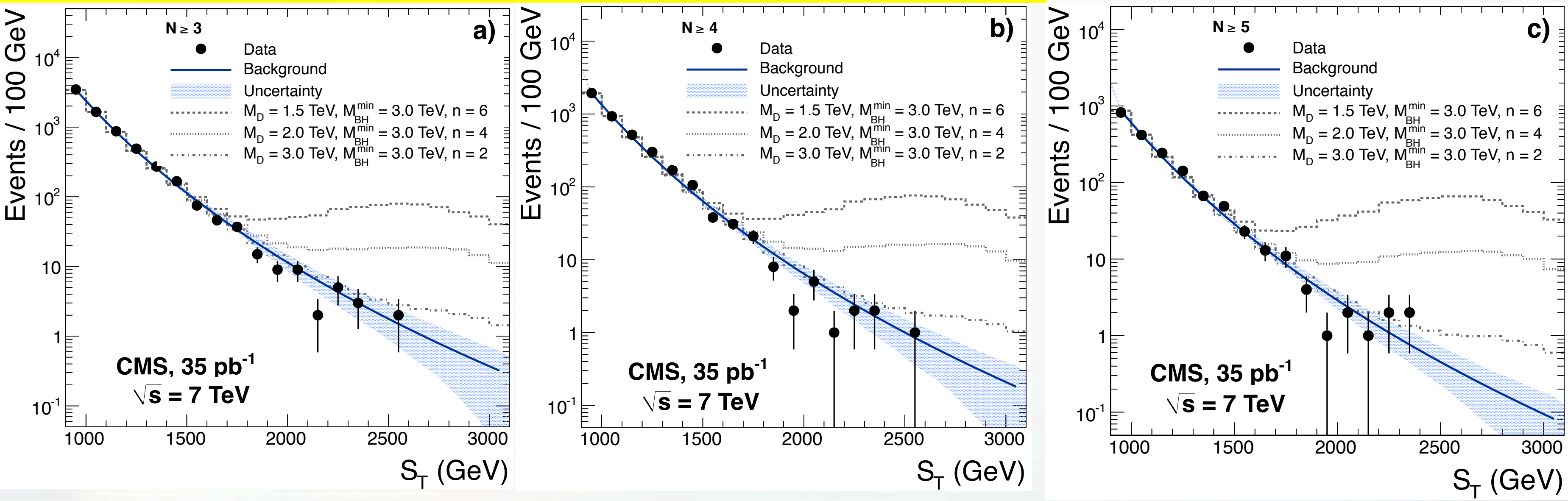

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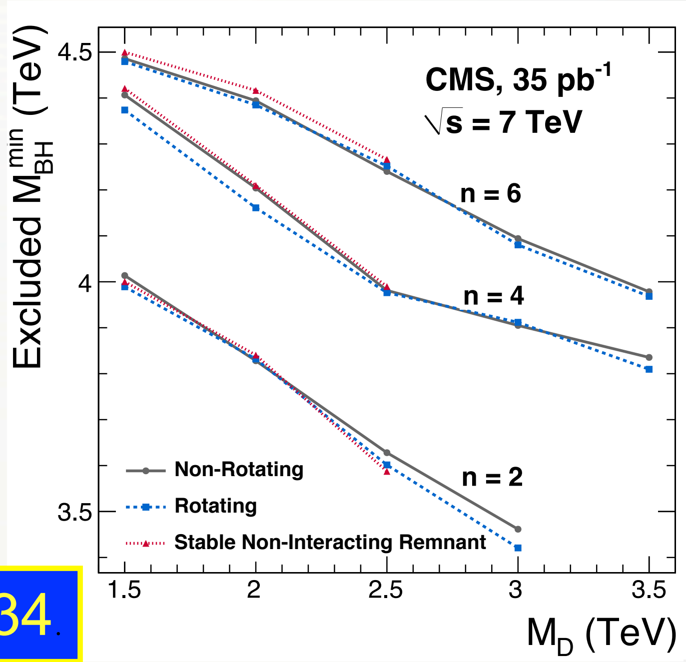

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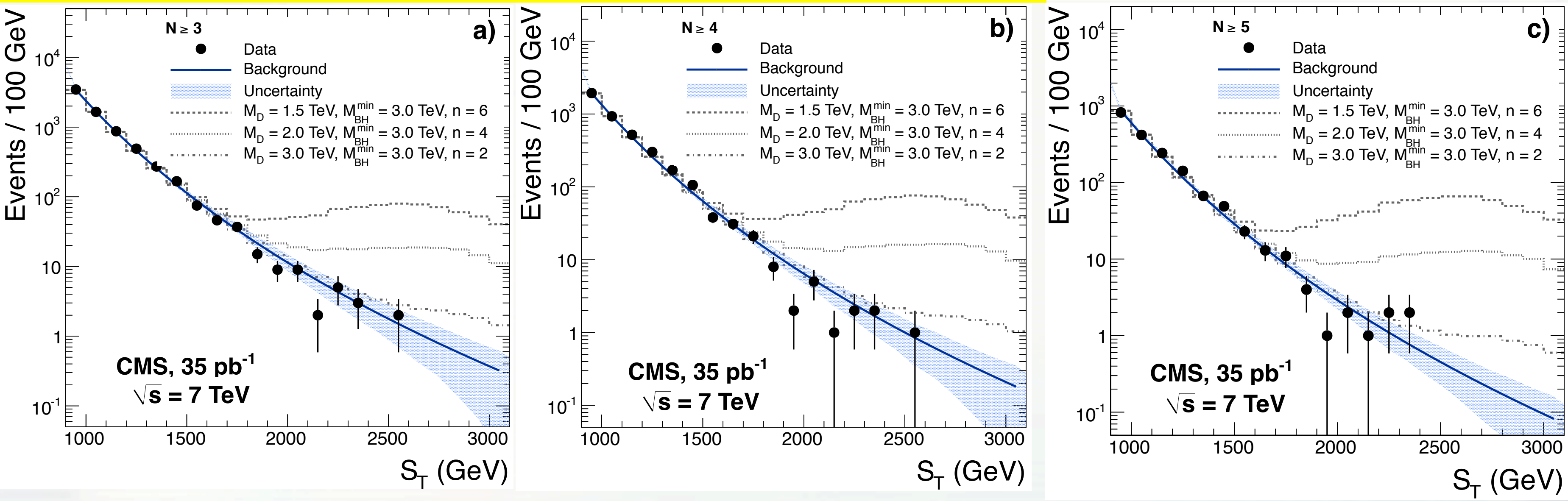

Model-Independent Limits

- Can also set generic model-independent limits on new physics decaying to high-mass, high-multiplicity final states, with $S_T > S_T^{min}$
- These limits, as a function of S_T^{min} are in a 0.1-1 pb range and can be used to probe more generic black hole models, including trapped surface losses, bulk radiation, etc.
- They are also useful for other models of new physics, e.g. heavy resonances decaying into multijet states

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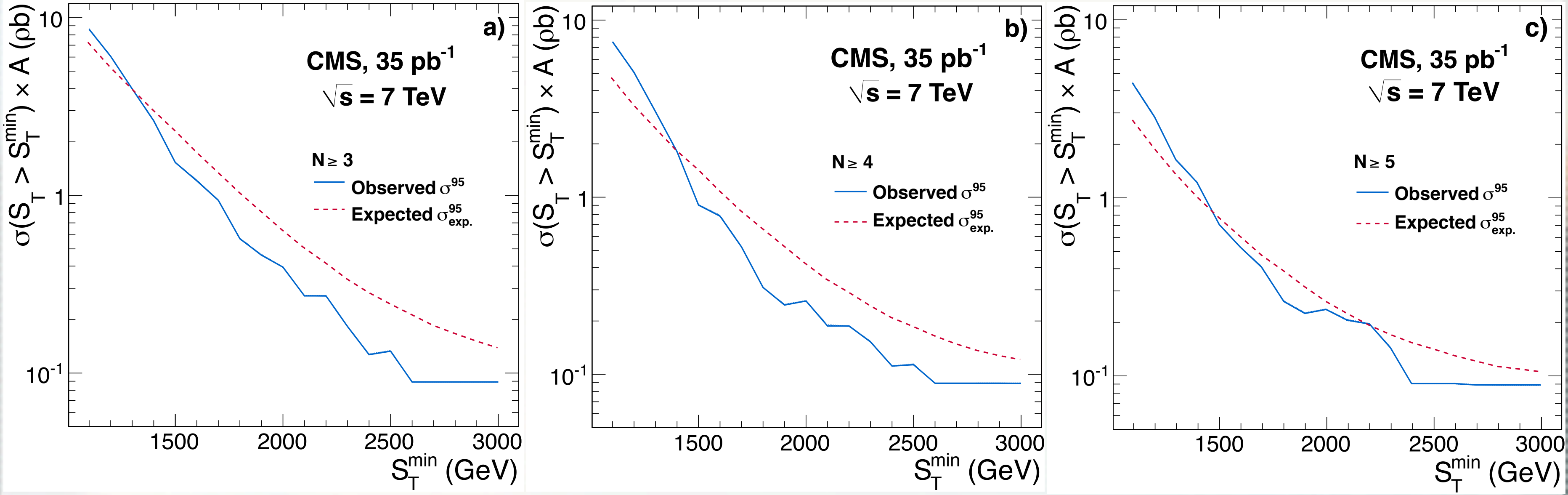
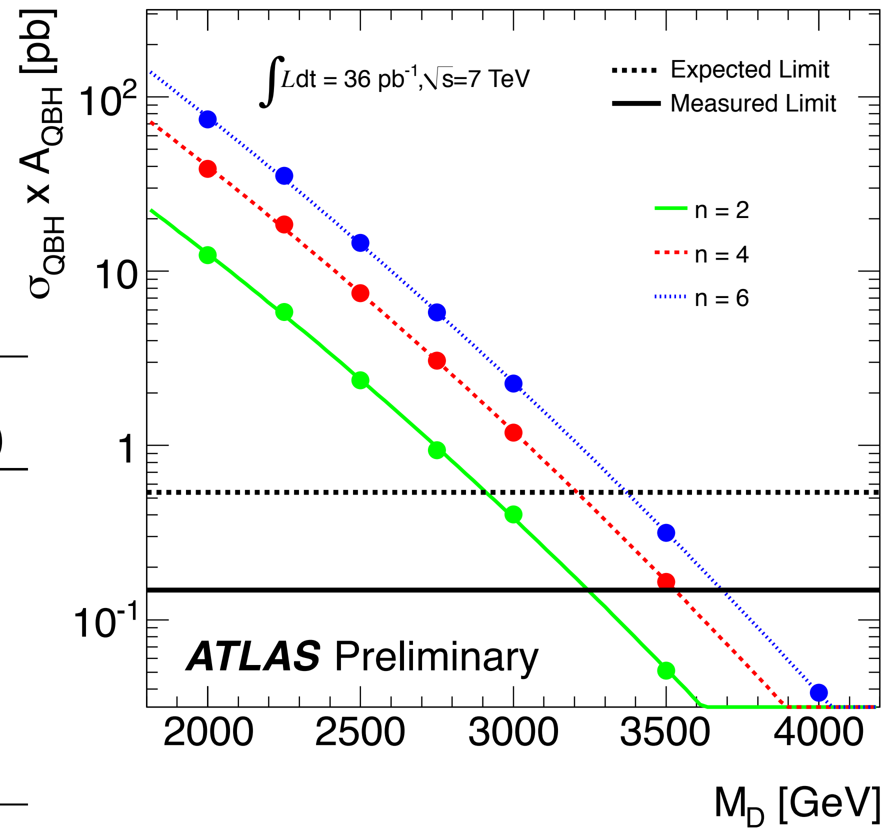


ATLAS Search for Quantum BH

- See Xavier's and Nina's talks for more details on QBH
- Decay very fast, possibly before thermalization
- Dominant decay mode: 2 jets (Meade-Randall model)
- Search for bumps in the dijet mass spectrum and an excess of central events using dijet angular distribution

arXiv:1103.3864, submitted to PLB



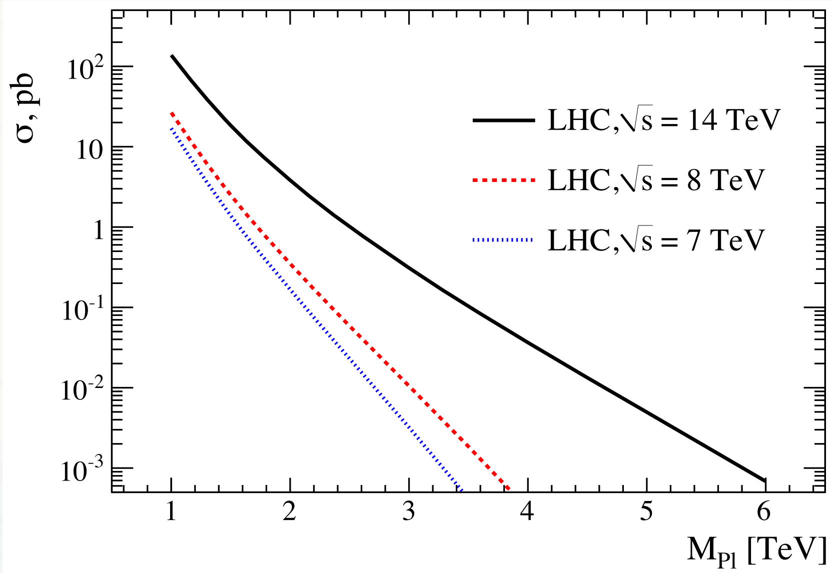
n Extra Dimensions	Expected Limit (TeV)	Observed Limit (TeV)
2	2.91	3.26
3	3.08	3.41
4	3.20	3.53
5	3.29	3.62
6	3.37	3.69
7	3.43	3.75

QBH and Vanishing Dimensions

- In some models, the space-time may be lower-dimensional at short distances, perhaps just 1+1-dimensional
- In this case, the black hole cross section is given by [Calmet/GL, arXiv:1008.3390]:

$$\sigma_{QBH} = \frac{1}{16\pi \bar{M}_P^2}\theta(\sqrt{\hat{s}} - \bar{M}_P).$$

- This is large cross section and the LHC will be able to probe this case as well



Kerr Black Holes

- Black holes produced in particle collisions generally have a non-zero angular momentum:

$$L = M_{\rm BH} R_S/2 = \frac{1}{2\sqrt{\pi}} \left[\frac{M_{\rm BH}}{M_{\rm Pl}}\right]^{\frac{n+2}{n=1}} \left[\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{1}{n+1}}$$

- While L is small for $M_{BH} = M_{Pl}$, it grows with M_{BH} and can reach ~10 (in the units of $\hbar$), which is non-negligible
- Such a spinning black hole is described by the Kerr solution and has an enhanced emission of gravitons (super-radiance)
- Unfortunately, the grey-body factor for spin-2 particles for the case of Kerr black hole in d > 3 dimensions has not been calculated, so it's hard to quantify the effect
- This is important for collider searches, as gravitons result in large missing transverse energy and reduced observable energy in the detector

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- If the scale of gravity is ~1 TeV, copious production of black holes at the LHC is likely to be an early and definitely most spectacular signature for extra dimensions
- Such a possibility would fulfill our dreams for Grand Unification of an ultimate kind: that of particle physics, astrophysics, and cosmology!

Thank You!